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Palynological analysis of Petro-Canada *et al.* Terra Nova K-18
Jeanne d'Arc Basin, Grand Banks of Newfoundland

G.L. Williams

2003

GEOLOGICAL SURVEY OF CANADA

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Marine Resources Geoscience Subdivision
Geological Survey of Canada (Atlantic), Dartmouth

2003

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Table of Contents

Well information	1
Introduction	1
Biostratigraphy	1
Paleoenvironments	5
Correlation of Palynology and Lithology	6
Summary	8
References	9
Figure 1	13
Appendix A	14

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G.S.C. Locality No.: D-259

Location: 46°46'22"N, 48°54'21"W

Elevation Sea level to R.T.: 24.3 m

Water Depth: 91.4 m

Total Depth: 3925 m

Spud Date: 19 July 1984

Interval Studied: 610-3925 m

Casing Points: 762 mm at 236 m; 508 mm at 601.5 m; 273 mm at 1980 m; 194 mm at 3776 m

Introduction

Petro-Canada *et al.* Terra Nova K-18 is in the southeastern part of the Jeanne d'Arc Basin, the Grand Banks of Newfoundland (McAlpine, 1990). K-18 is one of several wells drilled in the Terra Nova field, which is in production.

This study is based on the palynological analysis of 112 cuttings samples covering the interval 610-3925 m and 58 sidewall core samples from 616 to 3436 m. The Canada-Newfoundland Offshore Petroleum Board kindly loaned me the slides of the sidewall cores.

Biostratigraphy

My age determinations, based on dinoflagellate cysts (dinocysts), spores and pollen are in Figure 1. Ages are based on known stratigraphic ranges of dinocysts in European sections (Williams *et al.*, 1999, 2001, in press) and in other wells and core holes on the Grand Banks (Williams and Brideaux, 1975; Bujak-Davies, 1987; Williams *et al.*, 1990).

The deepest sample is at 3915-3925 m and contains the spore *Trilobosporites obsitus* (citations for individual species are given in Appendix 1), which has a first appearance datum (FAD) of Kimmeridgian, according to Bujak-Davies (1987). I also recorded the dinocyst *Occisucysta balios*, which has a last appearance datum (LAD) of 145.6 Ma according to Williams *et al.* (1999). Those authors used the timescale of Gradstein and Ogg (1996), so the LAD of *Occisucysta balios* is Kimmeridgian. In studies of other Grand Banks wells, I have not recorded *Occisucysta balios* above the early Kimmeridgian. On this basis I consider the sample at 3915-3925 m to be that age.

I include the interval 3550-3925 m in the early Kimmeridgian, based on the LAD of the dinocyst *Geiselodinium paemosum*. Williams and Bujak (1985) restricted this species to the Kimmeridgian, not taking it to the top. In other Jeanne d'Arc wells, I have noted that it seems to have an LAD of early Kimmeridgian. Other species restricted to this interval are the dinocysts *Adnatosphaeridium caulleryi* and *Leptodinium millioudii* and the spores *Striatella* #EAB Davies in Bujak-Davies (1987) and *Polycingulatisporites reduncus*.

From 3530 to 3010 m is mid Kimmeridgian, based on the relative abundance of species of the dinocyst *Epiplosphaera*, including *Epiplosphaera areolata* (common to abundant in several samples), *Epiplosphaera gochtii* and *Epiplosphaera bireticulata*. Williams *et al.* (1999) placed the LAD of *Epiplosphaera areolata* at 149 Ma, the top of the Kimmeridgian. In Jeanne d'Arc wells, *Epiplosphaera* species, which show a wide range of morphologies, also extend to the top of the Kimmeridgian but have a highest common occurrence within that stage. I am taking this to equate with the top of the mid Kimmeridgian. Other species with LADs in the interval 3530-3010 m are the dinocysts *Mendicodinium rugulatum*, *Rhynchodiniopsis cladophora* subsp. *hemipolyedrica* and *Systematophora vestita* and the spores *Cicatricosisporites* #EM Davies in Bujak-Davies (1987), which he considered to be Portlandian (Bujak-Davies, 1987).

The late Kimmeridgian, from 2990-2800 m, is characterized by the presence of the dinocysts *Egmontodinium expiratum*, *Histiophora ornata*, *Hystrichodinium voigtii*, *Hystrichodinium voigtii* subsp. "*brevispinum*", *Lanterna sportula* (abundant), *Muderongia* sp.A Davey and *Senoniasphaera jurassica*. Riding *et al.* (2001) considered *Muderongia* sp.A to be a taxonomic synonym of *Muderongia simplex*, whose last consistent occurrence they placed in the Kerberus ammonite zone of the early Portlandian. Williams *et al.* (1999) placed the LAD of *Senoniasphaera jurassica* at 144.2 Ma, just within the early Portlandian. In the Scotian Basin, Williams (1975) regarded the LAD of *Senoniasphaera jurassica* as denoting the top of the Kimmeridgian. I take this evidence and the consistent occurrence of *Epiplosphaera reticulata* in this interval as confirming the late Kimmeridgian age.

It is generally difficult to pick the Portlandian in the Jeanne d'Arc wells, since dinocyst abundances are low. Tentatively I include the interval 2780-2620 m in this stage, based on the LAD of the dinocyst *Lanterna bulgarica* at 2620-2630 m. Stover *et al.* (1996) considered the genus *Lanterna* to have its LAD at the Jurassic-Cretaceous boundary, which agrees with my data in the Jeanne d'Arc Basin. Other dinocyst taxa having LADs from 2620-2780 m are *Gochteodinia mutabilis*, *Dichadogonyaulax panneae* and *Sentusidinium rioultii*. The distinctive pollen *Corollina echinata* has its LAD at 2710-2720 m. The LAD of this species has been commonly used by oil company palynologists to denote the top of the Jurassic. The LAD of the spore *Striatella* #EE Davies in Bujak-Davies (1987) is at 2710-2720 m. Davies (op.cit.) considered the stratigraphic range of this species to be Portlandian to Berriasian.

The Berriasian section extends from 2600-2260 m. I have picked the top on the LADs of the dinocyst *Achomosphaera neptunii* and the spores *Cicatricosisporites crassistriatus*, *Cicatricosisporites purbeckensis*, *Cicatricosisporites versiformis* and *Leptolepidites psarosus*. *Cicatricosisporites purbeckensis* was described by Norris (1969) from the uppermost Jurassic of southern England. *Cicatricosisporites crassistriatus*, according to Davies in Bujak-Davies (1987) is restricted to the Berriasian of the Jeanne d'Arc Basin. In other Jeanne d'Arc Basin wells, including Whiterose N22 and Skua E-41, I have noted that the LAD of *Leptolepidites psarosus* is Berriasian. Therefore, it seems reasonable to consider 2600-2260 m to be Berriasian.

Davies in Williams *et al.* (1990) considered his *Striatella* #EJ subzone to be early Berriasian. In Terra Nova K-18, the LAD of the taxon is in the cuttings sample at 2470-2480 m. Thus, I am assigning 2600-2470 m to the early Berriasian and 2450-2270 m to the late Berriasian. *Aequitriradites baculatus*, a spore

that I find does not extend into post-Berriasian sediments in the Jeanne d'Arc Basin, has its LAD at 2440-2450 m.

I consider from 2257 to 1941? m to be Valanginian. The sidewall core at 2257 m contains the dinocyst *Cymososphaeridium validum*, which has an FAD at the base of the Valanginian according to Williams *et al.* (1999). Also in this sidewall is *Cassiculosphaeridia magna*, which I have found to be a consistent Valanginian marker in Jeanne d'Arc wells. The LADs of both *Cassiculosphaeridia magna* and *Phoberocysta neocomica* are at 1941 m. Williams (1975) defined a *Phoberocysta neocomica* Zone for the Scotian Shelf, which he considered Berriasian-Valanginian. Duxbury (1977, 2001) had Aptian records of this species, but it appears to have a much more restricted range in offshore eastern Canada. I question the top of the Valanginian because I only had sidewall cores. Presumably this reflects environmental control.

Other taxa with LADs in the Valanginian of Terra Nova K-18 are the dinocysts *Canningia cf. reticulata* sensu Duxbury 1977, *Dingodinium cerviculum*, *Discorsia nanna*, *Druggidium apicopaucicum*, *Kleithriasphaeridium fasciatum*, *Spiniferites dentatus*, *Heslertonella heslertonensis*. Spore LADs are *Coronatispora valdensis*, *Aequitriradites spinulosus*, *Cicatricosisporites annulatus* and *Cicatrocosisporites pseudotripartitus*.

Aptian sediments may immediately overlies the Valanginian and extend from 1904 to 1558 m. Unfortunately, I cannot confirm this. I do not have cuttings samples between 2140 and 1490 m and the quality of the slides from the sidewall cores is abysmal. Since there are no age diagnostic palynomorphs in the samples from 1904 to 1589 m, I do not give an age for this interval.

That there is Aptian at 1558 m is confirmed by the presence of *Cerbia tabulata*, whose LAD is considered to mark the Aptian, according to Williams (1975) and subsequent workers (e.g. Duxbury, 2001).

The sidewall core from 1546 m contains the dinocyst *Pseudoceratium eisenackii*, described by Davey (1969a) from the Albian, and *Microdinium veligerum*. Also present is *Surculosphaeridium longifurcatum*, which Williams *et al.* (1999) considered to have a latest Aptian LAD at 112 Ma. Overall, I consider these species to indicate an Albian age.

The Cenomanian may be restricted to a mere 18 metres or so, from 1500-1480 m. I base the Cenomanian age on the presence of the dinocysts *Cleistosphaeridium huguoniotii* and *Litosphaeridium siphoniphorum* in the cuttings sample from 1480-1490 m and *Psaligonyaulax deflandrei* and *Gonyaulacysta cassidata* in the 1482 m sidewall. Also, *Palaeohystrichophora infusorioides* in the 1500 m sidewall has an FAD of 100.27 Ma, according to Williams *et al.* (1999) and 99.85 Ma, according to Williams *et al.* (in press). I consider these data to be close enough to the basal Cenomanian to include 1500 m in that age.

I cannot separate the Turonian-Coniacian, which I extend from 1460 to 1338 m. The sidewall at 1338 m contains the LAD of the dinocysts *Florentinia ferox* and *Xenascus sarjeantii*. In Hibernia C-96, I found that the LAD of *Xenascus sarjeantii* was at the top of the Coniacian. Other dinocyst species with LADs in this interval are *Areoligera guembelii* at 1360-1370 m, *Hystrichosphaeridium bowerbankii* at 1367 m, *Florentinia radiculata* at 1402 m, *Oligosphaeridium pulcherrimum* at 1420 m and *Callaiosphaeridium asymmetricum* at 1450-1460 m. Williams (1975) erected the *Oligosphaeridium pulcherrimum* zone for the Coniacian. He considered the index species to have a Coniacian LAD in Scotian Shelf wells.

The base of the Coniacian may be at 1402 m, which sample contains *Isabelidium cooksoniae*. Williams and Bujak (1985) placed its FAD within the Turonian but their data was based on the concept

of a Coniacian of one million years. Further study may demonstrate that the FAD of *Isabelidinium cooksoniae* lies close to the Turonian-Coniacian boundary.

The cuttings sample at 1330-1340 m contains *Canningia reticulata* and *Raetiaedinium truncigerum*. Williams and Brideaux (1975) noted that *Raetiaedinium* (as *Hystrichosphaeridium*) *truncigerum* had an LAD in the Santonian. And Williams (1975) erected a *Raetiaedinium* (as *Hystrichosphaeridium*) *truncigerum* Zone, which he considered Santonian. This agrees with my designation.

The early Campanian, which extends from 1309-1286 m, is characterized by the LADs of the dinocysts *Kleithriasphaeridium loffrense* and *Surculosphaeridium? longifurcatum*. *Kleithriasphaeridium loffrense* has an LAD of 76.2 Ma and *Surculosphaeridium? longifurcatum* has an LAD of 81.68 Ma, according to Williams *et al.* (in press). These ages confirm an early Campanian age. *Palaeohystrichophora infusorioides* also has its LAD at 1286 m. Williams *et al.* (in press) consider this species to have an LAD close to the Campanian-Maastrichtian boundary.

Paleocene sediments appear to immediately overlie the Campanian section, but it is difficult to assign an age to the cuttings sample at 1370-1380 m. This sample contains abundant *Areoligera* cf. *medusettiformis* and *Cerodinium* is common. Both the above indicate Paleocene but do not allow differentiation of early or mid Paleocene. The answer would appear to lie in the LAD of the dinocyst *Spinidinium densispinatum* group, which occurs in the sample at 1180-1190 m. Williams *et al.* (1999) gave the LAD of *Spinidinium densispinatum* as 59.38 Ma, which is close to the Danian-Selandian boundary. I am therefore including 1280-1190 m in the Danian. Other dinocyst species with LADs in the Danian are *Cerodinium speciosum* and *Hystrichosphaeridium tubiferum*.

There is an abundance of *Palaeoperidinium pyrophorum* in the cuttings sample at 1240-1250 m. The LAD of *Palaeoperidinium pyrophorum* is 58.04 Ma (Williams *et al.*, in press), that's close to the top of the Selandian. In the Terra Nova K-18, the LAD of *Palaeoperidinium pyrophorum* is in the sidewall core at 1139 m. Other index taxa include *Palaeocystodinium bulliforme*, which has its LAD in the cuttings sample at 1150-1160 m and *Alisocysta margarita*, whose LAD occurs at 1120-1130 m. According to Williams *et al.* (in press), the LADs of *Alisocysta margarita* and *Palaeocystodinium bulliforme*, are 57.35 Ma and 57.9 Ma. The former is close to the top of the Selandian, the latter is at the Selandian-Thanetian boundary. Thus, I consider the interval 1169-1120 m to be Selandian.

The dinocyst species *Apectodinium augustum* in the cuttings sample at 1120-1130 m has a known stratigraphic range of 55.46 - 55 Ma (Williams *et al.*, in press), or within the late Paleocene. This explains the thin sliver of Thanetian (late Paleocene) from 1125-1110 m.

I consider from 1100 to 1060 m to be early Eocene (Ypresian). This is confirmed by the LAD of the dinocyst *Dracodinium condylos* at 1060-1070 m. Williams *et al.* (in press) gave the range of 52.5 - 51.5 Ma for this species, that's in the mid Ypresian. Also in the same sample is *Wilsonidium compactum*, described by Michoux (1985) from the type Lutetian (middle Eocene) of France. Thus, I place the Ypresian-Lutetian boundary at 1065 m.

Based on the LAD of *Glaphyrocysta divaricata*, the Lutetian extends from 1055 to 970 m. According to Williams *et al.* (1999), this species has an LAD at 44.5 Ma. *Rottnestia borussica*, which has an LAD in the early Lutetian in other Jeanne d'Arc wells, occurs in the sample at 1030-1040 m.

The middle Eocene has a twofold division, with the Lutetian being from 49 - 41.3 Ma and the Bartonian from 41.3 - 37 Ma (Gradstein and Ogg, 1996). I have designated 939-850 m as Bartonian, basing this on the LAD of the pollen *Extratropipollenites* in the cuttings sample from 850 to 860 m.

Extratirporopollenites has its LAD within the Bartonian in several wells in the Jeanne d'Arc Basin. Further confirmation comes from the LADs of *Cyclonephelium* sp.A Williams and Brideaux, 1975 at 880-890 m and the LAD of *Deflandrea hialina* at 910-920 m. Both these taxa have their LADs in the Bartonian in other wells in the Jeanne d'Arc Basin.

Priabonian or late Eocene sediments occur from 842-700 m, based on the consistent LAD of *Lentinia serrata* and *Lentinia "glabra"*. Williams *et al.* (1999) gave the LAD for *Lentinia serrata* as 33.5 Ma, the top of the late Eocene which equates with the top of the Priabonian.

From 677-610 m appears to be early Rupelian or early early Oligocene. The highest sample at 610-620 m contains *Operculodinium divergens*, which has an LAD of 31.97 Ma (Williams *et al.*, 1999). The lowest sample in this interval, a sidewall core at 677 m, contains the pollen grain *Gramineae*. There are a few Eocene record of the *Gramineae*, but most are Oligocene or younger.

A major problem with the cuttings samples from 1100 to 610 m is the high degree and variability of reworked material. There are Carboniferous spores, Cretaceous dinocysts and spores, but especially Late Cretaceous dinocysts, and early to mid Eocene dinocysts. Some of the Late Cretaceous dinocysts, such as *Laciniadinium arcticum* and *Chatangiella ditissima*, are reworked from higher latitudes. Manum and Cookson (1964) described *Laciniadinium arcticum* from the late Cretaceous of Ellef Ringes Island; *Chatangiella ditissima* was described from Campanian sediments of the Northwest Territories by McIntyre (1975). Presumably, Upper Cretaceous rocks to the northwest were being eroded and the material was transported by rivers to the Grand Banks, where it found a final resting place.

Paleoenvironments

Paleoenvironmental interpretations based on cuttings can be misleading but generalizations can be made. Sidewall core samples usually provide more reliable data. The Company slides were disappointing, however, yielding few or no palynomorphs. A striking feature of the lowermost samples from 3925-3340 m was the high proportion of degraded herbaceous material and well-preserved dinocysts. This, plus the common occurrence of the dinocyst *Cribrroperidinium*, indicate deposition in an inner neritic environment. Deeper water, more offshore conditions but still on the shelf, existed from 3790-3700 m, 3640-3650 m and 3430-3400 m. Abundant woody fragments at 3840-3850 m suggest a closer to shore paleoenvironment of high energy. A single sidewall core at 3436 m contained only the pollen *Corollina torosus*, indicative of fluctuating wet and dry, seasonal conditions according to Cornet and Traverse (1975).

There is a marked reduction in percentage of degraded herbaceous from 3310-3100 m and an increase in dinocysts, indicating continuing deposition in an inner neritic environment.

The cuttings sample at 3100-3110 m contains a higher pollen count but with good dinocyst representation. This suggests a shallowing, marginal marine setting. Again, there is a mixed signal from the sidewall cores, with the two at 3083 and 3074.7 m containing only *Corollina torosus*. The absence of dinocysts may indicate nonmarine episodes, although the cuttings samples continue to contain common, well-preserved specimens. There is an influx of degraded herbaceous at 3070-3080 m, followed by shallowing from 3040-3050 m.

Greater water depth and a more offshore setting occurred briefly at 3010-3020 m. This is marked by the dominance of the dinocysts and the increase in degraded herbaceous. But there is a rapid return to more marginal marine conditions from 2980-2860 m, with a strong indication of very close to shore to nonmarine episodes.

A flood of dinocysts, with species of *Cribroperidinium* at 2840-2810 m, supports an offshore inner neritic setting. However, *Cribroperidinium* has been regarded by some authors as denoting close to shore settings. There is another conundrum at 2794 m, where the sidewall core contains only the gymnosperm pollen *Pinuspollenites*. From 2780-2546.5 m, the paleoenvironments show little change, with little lateral migration in a marginal marine setting.

At 2530-2540 m, the assemblage includes the dinocysts *Cribroperidinium muderongense*, *Cribroperidinium orthoceras* and *Phoberocysta neocomica*, all regarded as inner shelf to marginal marine. The mixed dinocyst spore assemblages, usually with at least two of the above species, continue at 2260 m, with a possible nonmarine pulse at 2500-2510 m, and more marine conditions in the sidewall core at 2384 m, which contains the more open marine *Muderongia* (Monteil, 1991).

Increasing water depths and a more open marine setting is marked by a sidewall core at 2257 m but there is a return to marginal marine from 2240-2210 m. A brief, more open marine spell occurs from 2180-2110 m, then the signal is lost for most of the interval 2110-1628 m. The reason is the poor recovery from the sidewall cores and the unavailability of cuttings. One sidewall at 1904 m is devoid of dinocysts but contains a microforaminifera, presumably indicating open marine conditions. At 1589 and 1546 m, the mixed dinocyst/spore assemblage indicates a shallow marine paleoenvironment.

Deeper, open marine conditions are encountered at 1500 m, where the sidewall sample contains exclusively dinocysts and microforaminifera. This paleoenvironment persists to 1286 m, another sidewall core. There is a dramatic change in the cuttings sample from 1270-1280 m, which contains exclusively dinoflagellates, but of an unusual composition. The dominant species is *Areoligera* cf. *medusettiformis* but small forms of *Cerodinium* are also common. Powell *et al.* (1996) observed an analogous situation in samples from the type Thanetian of southern England. In the Pegwell Bay section, are three levels where *Areoligera* is superabundant and three levels where it is abundant. The authors considered these horizons to represent a restricted, high-energy, marginal marine setting typical of a transgressive regime. They interpreted the richest samples as being close to the most condensed interval or maximum flooding surface. Presumably the assemblages denote blooms. This would explain the common occurrences of *Cerodinium*. If this were a heterotrophic dinocyst, it should be attracted to and be successful where there are blooms of autotrophic taxa such as *Areoligera*. Successive *Areoligera* blooms occur at 1240-1250 m, 1180-1190 m, and 1150-1160 m.

A major signal related to the climatic regime occurs in the cuttings samples from 1120-1130 m and 1090-1100 m. These contain abundant specimens of the dinocyst *Apectodinium homomorphum*, which is considered to be a warmer-water species (Bujak and Brinkhuis, 1998). Crouch *et al.* (2001) have taken this a step further and shown that the onset of *Apectodinium*-dominated assemblages seem to be synchronous on a global scale. One occurred during the late Paleocene thermal maximum (LPTM) which lasted for about 220 ky at about 55 Ma. And it can be correlated with a negative carbon isotope excursion (CIE), a benthic foraminifera extinction event and the calcareous nannofossil zonation. The *Apectodinium* influx denotes higher sea-surface temperatures and a major increase in marginal-marine, surface-water productivity. And a marked decline in *Apectodinium* abundances towards the end of the LPTM may show a corresponding temperature decrease. Assuming the specimens are autochthonous, the paleoenvironments would not be dissimilar to those existing during the *Areoligera* blooms.

From 1070-873 m, the mixed dinocyst, pollen assemblages indicate an open marine neritic setting. Pollen dominate the interval from 873 to 820 m, from which I analysed two sidewalls and two cuttings. Strangely, this may represent deeper water, more oligotrophic conditions. From 812 to 600 m, the paleoenvironment is more or less uniformly open marine, although deeper water episodes are indicated at 760 and 600 m.

Correlation of Palynology and Lithology

The lithostratigraphy of the Terra Nova K-18 well was published by McAlpine (1989) and the lithostratigraphic terminology was formalized in McAlpine (1990). Throughout, I shall adhere to McAlpine (1989) for all depths and thicknesses. According to McAlpine (1989), the well bottomed in the Rankin Formation, which extends from 3926-3413 m. Therefore, the age of the Rankin is early to mid Kimmeridgian. McAlpine (1990) stated that the Rankin Formation was early Oxfordian-early Kimmeridgian at the type section in Rankin M-36, but could extend into the middle Kimmeridgian elsewhere. This agrees with my age determination for this formation in Terra Nova K-18, although McAlpine (1989, 1990) was designating the Tithonian as the youngest Jurassic stage. This is the more widely accepted approach but I still use the Portlandian, which is of shorter duration. This allows a satisfactory threefold subdivision of the Kimmeridgian and lets me correlate the Jeanne d'Arc section with southern England, geographically the logical choice. Bujak-Davies (1987) also use the Portlandian and recognize a threefold subdivision of the Kimmeridgian.

The Egret Member of the Rankin Formation, which is at 3790-3635 m, is exclusively early Kimmeridgian. This member was deposited primarily in an inner, but also partly outer, neritic environment.

Unconformably overlying the Rankin at 3413 m is the Jeanne d'Arc Formation, which extends to 3050 m. I consider this interval to be mid Kimmeridgian and do not recognize a hiatus. McAlpine (1990), who designated the K-18 section as the type section for the Jeanne d'Arc Formation, gave the age as Kimmeridgian-Tithonian. He noted, however, that the Bujak-Davies Group (1988) considered the formation to be consistently Kimmeridgian. Since the Bujak-Davies Group did not analyse any samples from Terra Nova K-18, the age given in McAlpine (1990) is by extrapolation from other Jeanne d'Arc wells.

The overlying Fortune Bay Shale, from 3050-2840 m, is 210 m thick. The interval 3050-2840 m, I consider late Kimmeridgian with the bottom 50 m being mid Kimmeridgian. McAlpine (1990) designated Terra Nova K-18 as the type section for the Fortune Bay Shale and considered it Tithonian. He acknowledged, however, that the Bujak-Davies Group (1988b) stated it was mid to late Kimmeridgian. As I have said above, the Bujak-Davies Group did not study Terra Nova K-18.

McAlpine (1989) included 2840-2371 m in the Hibernia Formation, with 2510-2371 m being assigned to the Hebron Well Member. Sequentially overlying the Hibernia are the "B" Marker from 2371-2305 m, the Catalina Formation from 2305-2204 m and the Whiterose Shale from 2204-1928 m. I consider the Hibernia Formation as latest Kimmeridgian-Berriasian, with the Hebron Well Member being Berriasian. McAlpine (1990) designated from 3839-4062 m in Hibernia K-14 as the type section for the Hibernia Formation. Since the palynology of this well has not been done by the Bujak-Davies Group, McAlpine based the age on the reference section in Hebron I-13. The age, according to Williamson (1987) and Ascoli (1988) is Tithonian-Berriasian. This is similar to my determination. The Hebron Well Member in the type section, Hebron I-13, is Berriasian according to McAlpine (1990). This age is based on both micropaleontology (Williamson, 1987; Ascoli, 1988) and palynology (E.H. Davies, pers. comm. to K.D. McAlpine, 1983). This agrees with my results.

In Terra Nova K-18, I consider the "B" marker to be late Berriasian, the Catalina Formation to be late Berriasian-early Valanginian, and the Whiterose Shale to be Valanginian. McAlpine (1990) gave a Valanginian age for the "B" Member at the type section, Ben Nevis I-45. But he considered its overall range late Berriasian-Valanginian, which shows some agreement with my ages.

The type section for the Catalina Formation is from 3300-3130 m in Hibernia O-35 (McAlpine, 1990).

E.H. Davies (pers. comm. to K.D. McAlpine, 1986) said that the age, based on palynology, was late Berriasian-Valanginian. This matches my results. My age for the overlying Whiterose Shale is more restricted than in McAlpine (1990), who generally considered it to be late Tithonian-Berriasian. Bujak-Davies (1988c) considered the unit's age to be late Kimmeridgian-Barremian at the type section, 3357-2728 m in Whiterose N-22. The problem in Terra Nova K-18 is that I do not have cuttings samples over the critical interval from 2110-1480 m and so cannot determine the age from above 1941 m to below 1558 m.

Conformably overlying the Whiterose Shale is the Eastern Shoals Formation (1928-1800 m), which is bounded by an unconformity at the top according to McAlpine (1989). The succeeding Avalon Formation (1800-1665 m) is in here unconformably overlain by the Ben Nevis Formation (1665-1590 m). I cannot confirm the above unconformities because of poor sample control. McAlpine (1990) considered the Eastern Shoals to be Hauterivian to Barremian, the Avalon to be late Barremian to late Aptian or early Albian, and the Ben Nevis to be late Aptian to early Albian. Because of inadequate sample control, I cannot give an age for these formations.

Succeeding the Ben Nevis is another unconformity-bounded sequence, the Nautilus Shale, which extends from 1590-1521 m (McAlpine, 1989). I consider this interval to be in part Aptian-early Albian. McAlpine (1990) in assigning an early Aptian to Albian-Cenomanian age to the Nautilus, stated that it potentially had the same age range as its lateral equivalents. Since these are the Avalon, Ben Nevis and Eider formations, the overall age would be Barremian to late Cenomanian-Turonian.

McAlpine (1989) recognized an unconformity at 1521 m, above which sequentially lie the Petrel Member of the Dawson Canyon Formation (1521-1460 m) and the rest of the Dawson Canyon Formation from 1460-1227 m. For the Jeanne d'Arc Basin, McAlpine (1990) believed the Dawson Canyon Formation to be late Cenomanian-Maastrichtian and the Petrel Member to be Turonian-Coniacian. In Terra Nova K-18, the Petrel is late Cenomanian to Turonian-Coniacian; the Dawson Canyon is late Cenomanian-Campanian.

The Banquereau Formation was erected by McIver (1972) for a predominantly mudstone sequence with locally abundant sandstone and siltstone on the Scotian Shelf. According to palynology, the type section from 1355-165 m in the well Sable Island C-67 is Campanian to Plio-Pleistocene. Hardy (1975) subdivided the Banquereau into four informal units but these appear to be locally restricted in the Scotian Basin. Subsequent authors, including McAlpine (1990), have extended the Banquereau to the Jeanne d'Arc Basin and recognized an informal subdivision, the South Mara unit. Sinclair (1988) was the first to refer to the South Mara member, which he defined as a set of submarine fans from 1895-1864 m in the South Mara C-13 well. He regarded them as reworked Upper Cretaceous sands. Although using the term South Mara in his lithostratigraphic column (his fig.8), McAlpine (1990) did not give any definition other than considering it basal Banquereau. McAlpine (1989), however, designated the interval 1227-1100 m in Terra Nova K-18 as the South Mara unit and 1227 to -1.0 as Banquereau. My age for the South Mara is Danian-Thauzetian early to late Paleocene. Thomas (1994, 1995) considered the South Mara unit to be Ypresian and deposited in bathyal waters at the type section, South Mara C-13.

Summary

Terra Nova K-18 has a Kimmeridgian-Valanginian section, which contains rich dinocyst, spore and pollen assemblages indicative of neritic environments. Within this interval are the type sections for the Jeanne d'Arc Formation (3413-3050 m) and the Fortune Bay Shale (3050-2840 m). Based on the dinocysts and spores, I have designated the Jeanne d'Arc as mid Kimmeridgian and the Fortune Bay as late Kimmeridgian. Because of the poor quality of the sidewall core samples and the unavailability of the cuttings samples, I could not determine the age of the Eastern Shoals, Avalon and Ben Nevis

formations. This leaves a major gap in our knowledge, especially as there are three unconformities according to McAlpine (1989).

In the Late Cretaceous, the relatively sparse palynomorph assemblages make age determinations more problematic. The Tertiary, however, contains abundant dinocysts that I can correlate with northwest European sections. In the Selandian-Thanelian (mid-late Paleocene), there are three *Areoligera* abundance peaks and one *Apectodinium* abundance peak. The *Areoligera* events relate to Thanelian maximum-flooding events seen in the type section. The *Apectodinium* event probably equates with the worldwide late Paleocene thermal maximum event (LPTM).

Another important result from my study of the Terra Nova K-18 palynomorphs is that I can extend the age of the South Mara unit down into the Selandian-Thanelian. This should provide further age control for this unit, which Deptuck *et al.* (in press) are formalizing. Such a step is necessary, because the Banquereau Formation is too all-encompassing. I'm convinced that with more detailed studies, we can further subdivide this formation in its younger part and elevate it to group status, a long overdue division.

Figure 1. Stratigraphy and paleoecology of Petro-Canada *et al.* Terra Nova K-18. The lithological picks are from McAlpine (1989).

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Appendix A

References for dinoflagellate citations are from Williams *et al.* (1998). References for spore and pollen citations are from Dettmann (1963) and Singh (1971). Informal taxa will be illustrated in one of the proposed palyatlas.

Achomosphaera neptuni (Eisenack, 1958a) Davey and Williams, 1966a
Achomosphaera neptuni subsp. “*brevispina*”
Adnatosphaeridium caulleryi (Deflandre, 1939a) Williams and Downie, 1969
Adnatosphaeridium multispinosum Williams and Downie, 1966c
Aequitriradites baculatus Doring, 1964
Aequitriradites spinulosus (Cookson and Dettmann, 1958) Cookson and Dettmann, 1961
Aequitriradites subverrucosus Doring, 1966
Alisocysta margarita (Harland, 1979a) Harland, 1979a
Amphorula delicata van Helden, 1986
Amphorula metaelliptica Dodekova, 1969
Apectodinium augustum (Harland, 1979c) Lentin and Williams, 1981
Apectodinium quinquelatum (Williams and Downie, 1966b) Costa and Downie, 1979
Areoligera guembelii Kirsch, 1991
Areoligera cf. *medusettiformis* O. Wetzel, 1933b
Areosphaeridium diktyoplokum (Klumpp, 1953) Eaton, 1971
Auritulinasporites deltaformis Burger, 1966
“*Axiodinium*” *ovale*
Baltisphaeridium “*scalenofurcatum*”
Batioladinium jaegeri (Alberti, 1961) Brideaux, 1975
Batioladinium longicornutum (Alberti, 1961) Brideaux, 1975
Batioladinium “*mutabilis*”
Callaiosphaeridium asymmetricum (Deflandre and Courteville, 1939) Davey and Williams, 1966b
Callialasporites dampieri (Balme, 1957) Sukh Dev, 1961
Callialasporites obrutus Norris, 1969
Callialasporites trilobatus (Balme) Sukh Dev, 1961
Camarozonosporites insignis Norris, 1967
Canningia reticulata Cookson and Eisenack, 1960b
Canningia cf. *reticulata* sensu Duxbury, 1977
Cantulodinium arthuriae van Helden, 1986
Cassiculosphaeridia magna Davey, 1974
Cerbia tabulata (Davey and Verdier, 1974) Below, 1981a
Cerebropollenites sp.
Cerebropollenites macroverrucosus (Thiergart) Schultz, 1967
Cerodinium “*glabrum*”
Cerodinium speciosum (Alberti 1959b) Lentin and Williams, 1987
Chatangiella ditissima (McIntyre, 1975) Lentin and Williams, 1976
Chatangiella tripartita (Cookson and Eisenack, 1960a) Lentin and Williams, 1976
Chlamydophorella nyei Cookson and Eisenack, 1958
Cicatricosisporites #EM Davies in Bujak-Davies, 1987
Cicatricosisporites #ES Davies in Bujak-Davies, 1987
Cicatricosisporites annulatus Archangelsky and Gamero, 1966
Cicatricosisporites crassistriatus Burger, 1966
Cicatricosisporites hughesii Dettmann, 1963
Cicatricosisporites pseudotripartitus (Bolkhovitina, 1961) Dettmann, 1963
Cicatricosisporites purbeckensis Norris, 1969

Cicatricosisporites subrotundus Brenner, 1963
Cicatricosisporites versiformis Doring, 1965
Cingutriteles "terranovae"
Circulodinium distinctum (Deflandre and Cookson, 1955) Jansonius, 1986
Circulodinium distinctum subsp. "*brevispinum*"
Circulodinium distinctum subsp. "*magnum*"
Cleistosphaeridium diversispinosum subsp. "*brevispinum*"
Cleistosphaeridium huguoniotii (Valensi, 1955a) Davey, 1969a
Cleistosphaeridium "terranovae"
Comasphaeridium cf. *cometes*
Contignisporites cooksoniae (Balme, 1957) Dettmann, 1963
Contignisporites fornicatus Dettmann, 1963
Contignisporites glebulentus Dettmann, 1963
Conv verrucosisporites exquisitus Singh, 1971
Conv verrucosisporites variverrucatus (Couper, 1958) Norris, 1969
Cordosphaeridium gracile (Eisenack, 1954b) Davey and Williams, 1966b
Cordosphaeridium cf. *eoinodes* (Eisenack, 1958a) Eisenack, 1963b
Corollina echinata (Burger, 1965) Dörhöfer, 1979
Corollina itunensis (Pocock, 1962) Cornet and Traverse, 1973
Corollina torosus (Reissinger) Klaus, 1960
Corollina vignollensis (Reyre, 1970)
Coronatisporites valdensis (Couper, 1958) Dettmann, 1963
Coronifera oceanica Cookson and Eisenack, 1958
Corrudinium incompositum (Drugg, 1970b) Stover and Evitt, 1978
Cribroperidinium longicorne (Downie, 1957) Lentin and Williams, 1985
Ctenidodinium elegantulum Millioud, 1969
Ctenidodinium schizoblutum (Norris, 1965) Lentin and Williams, 1973
Cyclonephelium sp. A Williams and Brideaux, 1975
Cyclonephelium sp. B Williams and Brideaux, 1975
Cyclonephelium hughesii Clarke and Verdier, 1967
Cyclonephelium vannophorum Davey, 1969a
Cymososphaeridium validum Davey, 1982b
Dapsilidinium laminaspinosum (Davey and Williams, 1966b) Lentin and Williams, 1981
Deflandrea denticulata Alberti, 1959b
Deflandrea heterophlycta Deflandre and Cookson, 1955
Densoisporites microrugulatus Brenner, 1963
Densosporites sp.
Dichadogonyaulax pannea (Norris, 1965) Sarjeant, 1969
Dingodinium cerviculum Cookson and Eisenack, 1958
Dingodinium "endocornum"
Dinogymnium Evitt *et al.*, 1967
Dinogymnium heterocostatum (Deflandre, 1936b) Evitt *et al.*, 1967
Dinopterygium cladoides Deflandre, 1935
Diphyes colligerum (Deflandre and Cookson, 1955) Cookson, 1965a
Discorsia nannus (Davey, 1974) Duxbury, 1977
Dissiliodinium sp.
Dracodinium condylos (Williams and Downie, 1966b) Costa and Downie, 1979
Dracodinium varielongitudum (Williams and Downie, 1966b) Costa and Downie, 1979
Druggidium apicopaucicum Habib, 1973
Egmontodinium expiratum Davey, 1982b
Egmontodinium toryna (Cookson and Eisenack, 1960b) Davey, 1979c
Endoscrinium campanula (Gocht, 1959) Vozzhennikova, 1967

Epiplosphaera areolata Klement, 1960
Epiplosphaera areolata subsp. “magna”
Epiplosphaera bireticulata Klement, 1960
Epiplosphaera gochtii (Fensome, 1979) Brenner, 1988
Epiplosphaera gochtii subsp. “magna”
Epiplosphaera reticulata (Valensi, 1953) Courtinat, 1989
Exochosphaeridium bifidum (Clarke and Verdier, 1967) Clarke *et al.*, 1968
Extratropopollenites spp.
Florentinia buspina (Davey and Verdier, 1976) Duxbury, 1980
Florentinia ferox (Deflandre, 1937b) Duxbury, 1980
Florentinia perforata Firth, 1993
Florentinia radiculata (Davey and Williams, 1966b) Davey and Verdier, 1973
Geiselodinium paemosum Drugg, 1978
Glaphyrocysta “*aexuberans*”
Glaphyrocysta divaricata (Williams and Downie, 1966c) Stover and Evitt, 1978
Glaphyrocysta intricata (Eaton, 1971) Stover and Evitt, 1978
Glaphyrocysta laciniiformis (Gerlach, 1961) Stover and Evitt, 1978
Glaphyrocysta ordinata (Williams and Downie, 1966c) Stover and Evitt, 1978
Glaphyrocysta “*preordinata*”
Glaphyrocysta spineta (Eaton, 1976) Stover and Evitt, 1978
Galphyroxysta texta (Bujak, 1976) Stover and Evitt, 1978
Glossodinium cf. *dimorphum* Ioannides *et al.*, 1977
Gochteodinia mutabilis (Riley in Fisher and Riley, 1980) Fisher and Riley, 1982
Gochteodinia “*unimutabilis*”
Gothanipollis Krutzsch, 1959
Gramineae spp.
Hafniasphaera hyalospinosa Hansen, 1977
Heslertonia heslertonensis (Neale and Sarjeant, 1962) Sarjeant, 1966b
Heteraulacacysta leptalea Eaton, 1976
Histiophora ornata Klement, 1960
Horologinella Cookson and Eisenack, 1962a
Hystrichodinium furcatum Alberti, 1961
Hystrichodinium pulchrum Deflandre, 1935
Hystrichodinium voigtii (Alberti, 1961) Davey, 1974
Hystrichodinium voigtii subsp. “*brevibrevispinum*”
Hystrichodinium voigtii subsp. “*brevispinum*”
Hystrichodinium voigtii subsp. *membranobrevispinum*
Hystrichokolpoma “*septarientonense*”
Hystrichosphaeridium bowerbankii Davey and Williams, 1966b
Hystrichosphaeridium petilum Gitmez, 1970
Hystrichosphaeridium salpingophorum Deflandre, 1935
Hystrichosphaeridium tubiferum (Ehrenberg, 1838) Deflandre, 1937b
Hystrichosphaeridium tubiferum subsp. “*perforatum*”
Hystrichosphaerina schindewolfii Alberti, 1961
Hystrichostrogylon sp.
Impardecispora #A Dörhöfer, 1977
Impardecisporites macrotuberculata (Kara Murza, 1957)
Impletosphaeridium insolitum Eaton, 1976
Inperturopollenites sp. #EA Davies, 1987
Isabelidinium cooksoniae (Alberti, 1959b) Lentin and Williams, 1977a
Ischyosporites amplireticosus Doring, 1973
Kiokansium williamsii C. Singh, 1983

Kleithriasphaeridium "aculeatum"
Kleithriasphaeridium fasciatum (Davey and Williams, 1966b) Davey, 1974
Kleithriasphaeridium "hibernium"
Kleithriasphaeridium loffrense Davey and Verdier, 1976
Kleithriasphaeridium simplicispinum (Davey and Williams, 1966b) Davey, 1974
Klukisporites foveolatus Pocock, 1964
Klukisporites pseudoreticulatus Couper, 1958
Laciniadinium arcticum (Manum and Cookson, 1964) Lentin and Williams, 1980
Lanterna bulgarica Dodekova, 1969
Lanterna sportula Dodekova, 1969
Lentinia "glabra"
Lentinia serrata Bujak in Bujak *et al.*, 1980
Leptodinium "amoco"
Leptodinium millioudii (Sarjeant, 1963c) Sarjeant, 1969
Leptolepidites psarosus Norris, 1969
Litosphaeridium siphoniphorum (Cookson and Eisenack, 1958) Davey and Williams, 1966b
Lycopodiacidites cerniipites (Ross, 1949) Norris, 1969
Lycopodiumsporites austroclavatidites (Cookson, 1954) Potonié, 1956
Meiourugonyaulax stoveri Millioud, 1969
Membranophoridium aspinatum Gerlach, 1961
Mendicodinium reticulatum Morgenroth, 1970
Mendicodinium "rugulatum"
Microdinium irregulare Clarke and Verdier, 1967
Microdinium veligerum (Deflandre, 1937b) Davey, 1969a
"Muderongia sp.A Davey, 1979
Muderongia staurota Sarjeant, 1966c
Nodosporites babsae (Brenner, 1963) Davies, 1985
Nyktericysta vitrea (Duxbury, 1983) Bint, 1986
Occisucysta balios Gitmez, 1970
Occisucysta "distincta"
Occisucysta tentoria Duxbury, 1977
Odontochitina costata Alberti, 1961
Oligosphaeridium asterigerum (Gocht, 1959) Davey and Williams, 1969
Oligosphaeridium complex (White, 1842) Davey and Williams, 1966b
Oligosphaeridium diluculum Davey, 1982b
Oligosphaeridium cf. patulum Riding and Thomas, 1988
Oligosphaeridium pulcherrimum (Deflandre and Cookson, 1955)
Oligosphaeridium "terranovae"
Operculodinium divergens (Eisenack, 1954b) Stover and Evitt, 1978
Palaeocystodinium bulliforme Ioannides, 1986
Palaeohystrichophora infusorioides Deflandre, 1935
Palaeoperidinium pyrophorum (Ehrenberg, 1838) Sarjeant, 1967b
Paralecaniella indentata (Deflandre and Cookson, 1955) Cookson and Eisenack, 1970b
Parvisaccites sp.
Perisseiasphaeridium ingegerdiae Nøhr-Hansen, 1986
Pervosphaeridium monasteriense Yun Hyesu, 1981
Phoberocysta neocomica (Gocht, 1957) Millioud, 1969
Phoberocysta neocomica subsp. *cruciformis* (Gocht, 1957) Lentin and Williams, 1973
Phthanoperidinium amoenum Drugg and Loeblich Jr., 1967
Phthanoperidinium coreoides (Benedek, 1972) Lentin and Williams, 1976
Phthanoperidinium crenulatum (de Coninck, 1975) Lentin and Williams, 1977b
Phthanoperidinium "hibernium"

Phthanoperidinium levimurum Bujak in Bujak *et al.*, 1980
Phthanoperidinium multispinum Bujak in Bujak *et al.*, 1980
Pilosisorites verus Delcourt and Sprumont, 1955
Pilosisorites sp.A Bujak and Williams, 1977
Pilosisorites trichopapillosus (Thiergart) Delcourt and Sprumont, 1955
Plicatella bilateralis (Singh, 1971) Dörhöfer, 1977
Plicatella potomacensis (Brenner, 1963) Davies, 1985
Polycingulatisporites reduncus (Bolkhovitina, 1953) Playford and Dettmann, 1965
Prolixosphaeridium granulosum (Deflandre, 1937b) Davey *et al.*, 1966
Psalinonyaulax deflandrei Sarjeant, 1966b
Pseudoceratium eisenackii (Davey, 1969a) Bint, 1986
Pseudoceratium pelliferum Gocht, 1957
Pterospermopsis helios Sarjeant, 1959
Raetiaedinium truncigerum (Deflandre, 1937b) Kirsch, 1991
Rhynchodiniopsis cladophora subsp. *hemipolyedrica* (Klement, 1960) Below, 1981a
Rottnestia borussica (Eisenack, 1954b) Cookson and Eisenack, 1961b
Rubinella major (Couper, 1958) Norris, 1969 sensu Norris, 1969
Rugubivesiculites rugosus Pierce, 1961
Samlandia chlamydotheca Eisenack, 1954b
Schematophora speciosa Deflandre and Cookson, 1955
Scriniodinium crystallinum (Deflandre, 1939a) Klement, 1960
Scriniodinium inritibile Riley in Fisher and Riley, 1980
Senegalinium sp.
Senoniasphaera jurassica (Gitmez and Sarjeant, 1972) Lentin and Williams, 1976
Sentusidinium rioultii (Sarjeant, 1968) Stover and Sarjeant, 1978
Sentusidinium rioultii subsp. “*minispinum*”
Sequoapollenites sp.
Spinidinium echinoideum (Cookson and Eisenack, 1960a) Lentin and Williams, 1976
Spiniferites sp. “W”
Spiniferites dentatus (Gocht, 1959) Lentin and Williams, 1973
Spiniferites “duplifurcatus”
Spiniferites “procerus”
Spiniferites pseudofurcatus subsp. “*brevispinus*”
Spiniferites speciosus (Deflandre, 1937b) Sarjeant, 1970
Spongodinium delitiense (Ehrenberg, 1838) Deflandre, 1936b
Striatella #EAB Davies in Bujak-Davies, 1987
Striatella #EE Davies in Bujak-Davies, 1987
Striatella #EJ Davies in Bujak-Davies, 1987
Striatella #ET Davies in Bujak-Davies, 1987
Surculosphaeridium longifurcatum (Firtion, 1952) Davey *et al.*, 1966
Surculosphaeridium cf. *longifurcatum*
Systematophora complicata Neale and Sarjeant, 1962
Systematophora “diversispinosa”
Systematophora penicillata (Ehrenberg, 1843b) Sarjeant, 1980a
Systematophora “scotensis”
Systematophora silybum Davey, 1979a
Systematophora valensii (Sarjeant, 1960a) Sarjeant, 1961b
Systematophora vestita (Deflandre, 1939a) Davey, 1982b
“*Talladinium*” *coleothryptum*
Tanyosphaeridium magdali (Drugg, 1967) Heisecke, 1970
Tanyosphaeridium variecalamum Davey and Williams, 1966b
Tectatodinium pellitum Wall, 1967

Trichodinium castanea Deflandre, 1935
Trilobosporites apiverrucatus Couper, 1958
Trilobosporites bernissartensis (Delcourt and Sprumont, 1959) Potonié, 1956
Trilobosporites granulatus Doring, 1965
Trilobosporites marylandensis Brenner, 1963
Trilobosporites obsitus Norris, 1969
Triquitrites spp.
Trithyrodinium “*granulatum*”
Trithyrodinium “*scabratum*”
Tubotuberella apatela (Cookson and Eisenack, 1960b) Ioannides *et al.*, 1977
Turbiosphaera filosa (Wilson, 1967a) Archangelsky, 1969a
Uvaesporites glomeratus Doring, 1965
Vitreisporites pallidus (Reissinger) Potonié, 1960
Wetziella gochtii Costa and Downie, 1976
Wilsonidium compactum Michoux, 1988
Xenascus australiensis Cookson and Eisenack, 1969
Xenascus ceratioides (Deflandre, 1937b) Lentin and Williams, 1973
Xenascus ceratioides subsp. “*perforatus*”
Xenascus sarjeantii (Corradini, 1973) Stover and Evitt, 1978
Xenascus serpaglio (Corradini, 1973) Stover and Evitt, 1978
Xiphophoridium alatum (Cookson and Eisenack, 1962b) Sarjeant, 1966b