



GEOLOGICAL SURVEY OF CANADA

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Palynology, age, correlation and paleoclimatology from JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well and the significance for gas hydrates: a new approach

James M. White

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Abstract

The 1150 m deep JAPEX/JNOC/GSC Mallik 2L-38 research well was drilled in 1998 to investigate gas hydrate deposits previously identified in Mallik L-38. For the study of the palynostratigraphy and paleoclimatology of the Beaufort-Mackenzie Basin, Mallik 2L-38 provides an uncommon opportunity to analyse core and high quality cuttings that span a 480 m section of upper Paleogene sediment. A detailed, quantitative palynological analysis is reported herein and percentage diagrams are provided for each taxon. One hundred and twenty five taxa are illustrated.

Recycling of palynomorphs from Cretaceous and older Paleogene strata can confuse age determination. A criterion proposed to evaluate recycling is an assessment of chaotic patterns versus coherent, explicable patterns. Relative abundance plots and statistical techniques are used to distinguish between chaotic versus coherent patterns, hence evidence for and against recycling. These techniques do not produce a definitive assessment for any individual taxon, but demonstrate the coherence of the overall palynological record. It is concluded that the palynomorphs provide a biostratigraphic record suitable for the determination of age and depositional environment of the rocks.

The proposed age and correlation for Mallik 2L-38 assigns the interval between 1150 m and a disconformity at 926.5 m to the Late Eocene, and the interval between that disconformity and the top of the cuttings at 670 m to the Oligocene and possibly earliest Miocene. It is concluded that some 1000 m more sediment accumulated during the Eocene in Mallik 2L-38 than evinced by micropaleontology in adjacent Mallik L-38. This is because the foraminiferal top of the *Haplophragmoides richardsensis* zone in Mallik L-38 ends in a shallowing-upwards marine sequence, changing to a continental facies with minor marine incursions, yielding an environment unsuitable for diagnostic foraminifera, but this continental environment was rich in pollen and spores. Placing these age interpretations beside the seismic sequence interpretations implies that the Kugmallit Sequence contains sediment of Late Eocene age. This argues that the Richards and Kugmallit formations must be in part facies equivalents in the nearshore, although in the offshore Kugmallit overlies Richards.

Palynological correlation to the Caribou Hills is problematic, but the Mallik 2L-38 disconformity at 926.5 m may be equivalent to the Caribou Hills Embryophyte Zone 4b - 4c unconformity, or perhaps to some interval within CHE4c. In correlation to Adgo F-28, the Mallik 2L-38 disconformity at 926.5 m probably correlates to the top of the *Integricarpus* zone.

Experimental proxies for paleoclimatic temperature are provided by four ratios of pollen taxa in an attempt to improve the age determinations by correlation to the North Atlantic foraminiferal $\delta^{18}\text{O}$ curve. Two ratios suggest that a cold climatic episode coincided with the deposition of sediment at the top of the cored interval near 886 m in Mallik 2L-38, probably correlating with the basal Oligocene portion of the North Atlantic foraminiferal $\delta^{18}\text{O}$ curve. This suggests a relationship between this climatic event and the top of the gas hydrate hosting

interval, which is most likely explained by the climatic effect on sedimentation.

The taxonomy of triprojectate pollens, *Integricorpus* and *Parviprojectus*, are considered and it is proposed to provisionally adopt “*Integricorpus* sp. cf. *I. reticulatus*” for the reticulate form and retain usage of “*Parviprojectus* A” for the striate form. A new species of triprojectate pollen, named *Striatocorpus sweetii*, is identified in Mallik 2L-38 in Late Eocene sediment.

Introduction

The Mallik L-38 exploration well, drilled in 1972 in the Mackenzie Delta of Arctic Canada ([Figure 1](#)), penetrated gas hydrates (Bily and Dick, 1974). The geological, geochemical, geophysical and engineering properties associated with this gas hydrate accumulation were investigated by geophysical surveys and by the subsequent drilling and analysis of the JAPEX/JNOC/GSC Mallik 2L-38 well (69° 27' 40.71" N, 134° 39' 30.37" W, TD 1150 m), located only 150 m distant from the original L-38 well, in February-March, 1998. All depth are measured from the kelly bushing, 8.31 m above sea level (Ohara et al., 1999).

As a result of the Mallik 2L-38 research program and previous work, Collett et al. (1999a,b) have estimated that up to $187,178 \times 10^6 \text{ m}^3$ of gas is trapped as hydrates in 4 fields on Richards Island, with $2.93 - 4.15 \times 10^9 \text{ m}^3$ within the 1 km^2 area surrounding the Mallik 2L-38 site. In 2001-02, Mallik 3L-, 4L- and 5L- 38 were drilled adjacent to Mallik 2L-38 to improve scientific and technological knowledge concerning gas hydrates (Dallimore et al., 2002).

As part of the Mallik 2L-38 program, paleontological investigations (McNeil, 1999; Kurita and Uchida, 1999; White, 1999) were conducted to determine the age and environment of deposition of the rocks penetrated by the well. This study is a more detailed analysis, documentation, and revision of the palynological results reported by White (1999). Reported here are the distributions of pollen and spores from the cored intervals between 110.11 to 118.35 m and 886.38 to 951.29 m, and from cuttings between 670 to 880 m and 960 to 1150 m. The cored interval between 886.38 to 952.29 m hosts gas hydrates (Jenner et al., 1999).

Tectonic setting

The Mallik 2L-23 site sits in a parallel array of southwest-northeast trending faults of the Taglu Fault Zone (TFZ). The TFZ extends from the Outer Hinge Line marking the southeastern edge of the greater than 5 km thick, Tertiary fill of the Beaufort-Mackenzie Basin ([Figure 1](#)). On the southeast side of the TFZ are older rocks of the continental margin, dominantly of Mesozoic and Paleozoic age. Extensional faults in the TFZ were developed predominantly in the Eocene, during deposition of the Taglu and Richards sequences. Richards Sequence strata on the downthrown side of some faults are thickened and rotated, indicating some Late Eocene syndepositional fault displacement. Late Miocene, northeast trending compression resulted in some reverse faulting in the Taglu Fault Zone (Lane and Dietrich, 1995).

Sequences

Several sequence stratigraphic subdivisions have been proposed for the Mallik L-38 and 2L-38 wells ([Figure 2](#)). Sequence tops for the original Mallik L-38 well have been determined by foraminifera by McNeil and Birchard (1989), who recognized the Iperk and Kugmallit sequences within the 1150 m depth of the 2L-38 well. Based on regional geological correlations, log character, seismic profiles and to some extent on paleontology, Dixon (1990) recognized a probable Mackenzie Bay Sequence in the upper portion of what McNeil and Birchard (1989) called Kugmallit Sequence. Both schemes recognized the presence of the marine Richards Sequence at 1934 m in L-38, indicated by the occurrence of *Jadammina statuminis* (McNeil and Birchard, 1989).

For the Mallik 2L-38 study, Collett and Dallimore (1998) identified the Iperk, Mackenzie Bay and Kugmallit sequences, differing chiefly from previously cited studies by the 932 m pick for the top of the Kugmallit Sequence. After sedimentological study of the Mallik 2L-38 core, Jenner et al. (1999) tentatively placed the Mackenzie Bay/ Kugmallit contact in 2L-38 at 926.5 m, referred to herein as a disconformity.

Previous Age Interpretation and Recycling

The paleontological analyses of the Mallik 2L-38 well foraminifera by McNeil (1999), dinoflagellates by Kurita and Uchida (1999) and pollen and spores by White (1999) did not result in a consensus regarding the age of the penetrated rocks. McNeil (1999), in his analysis of the foraminifera in Mallik 2L-38, observed significant recycling of Cretaceous agglutinated foraminifera. He concluded that all the foraminifers were recycled, with the possible exception of a single specimen of *Haplophragmoides carinatus*? at 1100 m, that, if in place, would imply a late Eocene to middle Miocene age at 1100 m. McNeil (1999) also observed that the lithology of the section below 670 m was typical of the Oligocene Kugmallit Sequence. Thus, McNeil (1999) concluded that the foraminifers, dinoflagellates and pollen and spores were recycled, and that the palynological interpretation by White (1999) that the Richards and Taglu sequences were present between 930 and 1150 m was “highly unlikely”. The sediment and core samples below 670 m were tentatively considered to represent a proximal facies of the Kugmallit Sequence, of Oligocene age.

Kurita and Uchida (1999) found that Middle to Upper Cretaceous dinoflagellates were broadly distributed through the Mallik 2L-38 well. Dinoflagellates of Paleocene to Eocene age were found exclusively within the interval 945.21 to 948.16 m, and suggested to Kurita and Uchida a similarity to an assemblage described by Dietrich et al. (1989) from the Taglu Sequence in the western Beaufort Sea. Because of the accepted assignment of that interval to the Kugmallit Sequence, they concluded that these dinoflagellates were recycled.

White (1999) recognized recycled pollen, spores and dinoflagellates, but argued that the *in situ* pollen and spores provided a primary biostratigraphic signal, and proposed an age interpretation for the section below 995 m to be of Early to Middle Eocene age, from 995 to 930 m to be Late Eocene, 930 to 897 to be probably Late Eocene, and 897 to 670 m to be between

Late Eocene and Late Miocene age. Sequence affiliations that were suggested were based on the age determinations, using the stratigraphic assumption that an Oligocene age would indicate the Kugmallit Sequence, a Late Eocene age the Richards Sequence, and an Early to Middle Eocene age, the upper Taglu and Richards sequences.

In the following discussion, White's (1999) age interpretation is revised, such that all sediment from 670 to 926.5 m is considered to be of probable Early Miocene - Oligocene age, and sediment below 926.5 m to TD is considered to be of Late Eocene age. The biostratigraphy is presented quantitatively and it is argued by biostratigraphic and statistical arguments that the palynomorph record provides a primary palynostratigraphic signal, in spite of some recycling.

Lithology of Mallik 2L-38 Well

Detailed sedimentological descriptions are not available throughout the Mallik 2L-38 well because sedimentology focused on the gas hydrate-bearing rocks. The 110.11-118.35 m cored interval was described only by McNeil (1999).

The sedimentology and geophysical properties of rock below 850 m is described by Collett et al. (1999a). Detailed description of the gas hydrate-hosting cored interval, 886 - 952 m, is found in Jenner et al. (1999), who note that the core between 891 and 925 m has thick beds of sand to clayey sand, with finer grained material below (Jenner et al., 1999). McNeil (1999) also provides lithologic information and compares the cored interval with overlying rock through his analysis of the washed residues of cuttings and core.

The washed residues for the 886 to 952 m cored interval (Cores 12-24) yielded very few microfossils (McNeil, 1999): residues consisted of, " ... fine grains of quartz and chert with pyrite commonly encrusting grains and cementing small (≤ 2 mm) clumps of sediment. An abundance of dark brown to black, woody, lignitic/coaly material and rare amber was also characteristic of most samples." Rare plant remains included sclerotium of the fungus *Cennococcum geophilum*, the algal cyst *Leiosphaeridia*, seeds of *Typha* sp., (cattails), the megaspore *Arcelites nudus*, seed casings, and *Tasmanites* and *Dictyothylakos* (McNeil, 1999). McNeil (1999) observed that lithology is similar to that found in the proximal facies of the Kugmallit Sequence in the Mallik L-38 and P-09. McNeil (1999) also noted that the washed residues of cuttings from 670–870 and 960–1140 m were lithologically similar to the cores from 886–952 m, although cuttings showed a conspicuous increase in grain size. This may be because the core was sampled for finer-grained material (McNeil, 1999).

The change from a cutting sample at 870 m to a core sample at 886.4 m (top of Core 12) is significant for palynological interpretation because of inflections in the Pinaceae percentages (below). McNeil (1999, fig. 2) noted a difference between the 870 m sample and the 886.4 m sample in the fine to coarse grain size above, and finer grain size below. However, this may be an artifact of sampling, as discussed above. Thus, no observations are available that clearly resolve whether there is a lithological boundary between the cored interval, ca. 886 m, and the overlying cuttings. However, the top of the occurrence of gas hydrates may suggest some

lithological boundary.

Methods

Drilling and Palynological Sampling

Drilling operations determined paleontological sample recovery. Caliper logs show an enlarged well bore above the casing at 667 m (Ohara et al., 1999) indicating extensive caving, so that the only samples analysed above that depth were from the short core interval from 111.12 to 118.34 m. The well was cased to 667 m, and then the drilling mud was replaced with new mud. Below the 667 m casing, the caliper log indicates that the hole is near nominal gauge (Ohara et al., 1999). Thus, cuttings between 670 and 886 m were taken from the portion of the hole that had minimal caving problems.

At 886 m the hole was cleaned of gravel from the formation or that was chased down hole by drilling operations. Cores 12 to 24 were taken in the gas hydrate bearing zone, yielding a total of 37 m of recovered core, in an interval spanning the 886.4 to 952.6 m interval (this interval may be referred to in the following discussion as “the cored interval” or “the core”). Cuttings below 952 to 1150 m (TD) were also from a nominal gauge hole and thus are relatively free of caving. Hence, in spite of some drilling problems, the Mallik 2L-38 research hole has provided subsurface samples of high quality which are not normally obtainable from industrial drilling operations. Better quality samples could only be obtained from continuous core, or from outcrop.

Palynological Analysis

Paleontological samples from core and cuttings were obtained during drilling operations and during lithological analysis of the core (Dallimore et al., 1999; Ohara et al., 1999). Cores 1 and 2, 110.11 to 118.35 m, yielded ten useful palynological samples. Core 8, 173.56 to 175.42 m, yielded three barren samples. Sampling and palynological analysis was concentrated on cores 12 to 24 from the gas hydrate hosting zone, between 886 and 952 m. Here, thirty five samples were analysed from fine grained, organic rich beds. Also analysed were forty-two cuttings samples representing 10 m intervals between 670 (below the casing) and 1150 m (TD), excluding the intervals where core was available.

Core samples are referred to here by their depth midpoint although most spanned a 2 cm interval. Cuttings samples are from 10 m increments. The ratio of 2 cm (0.02 m) to 10 m makes a difference in sampling precision of approximately 500 times between core and cuttings. Assuming a more or less constant sedimentation rate, that implies the same difference in chronological resolution between core and cutting samples.

Palynological samples of 9 to 15 grams were macerated using standard HCl, HF treatment and a light, cold Javex treatment. Samples were cleaned by ultrasonic screening with screens of 180 μm and 7 μm nominal openings, yielding a fraction for analysis between ca. 254 and 10 μm (the diagonals of the nominal mesh sizes).

Samples were weighted and *Lycopodium* added by tablets (Batch 212761) to permit measurements of pollen concentration in the preparations (Benninghoff, 1962). During the first processing run, the sample weights and number of tablets added were omitted on some of the laboratory record sheets, and have been estimated by reference to the samples processed in the same batch. Thus, for samples 886.38 m to 903.01 m (inclusive) and 906.58 m the concentration values are based on sample weights of 9 g and the addition of one *Lycopodium* tablet. The concentration value estimated by these assumptions is a middle concentration value, which would be reduced to perhaps two thirds if more sample was taken, or doubled if two tablets were added.

Although sedimentological reports (Jenner et al., 1999) indicate the presence of some detrital coal in the 886-952 m core samples, only one sample (942.72 - .74 m) had a “?coal” note attached on the laboratory processing sheet (GSC Calgary Palynological Lab number P4364-27, Curation number C-400730). Only a portion of the coal is broken down by the processing techniques used, so that palynomorphs from the possible coal would not contributed much to the sample assemblage analysed. No sample remained of P4367-27, so that the “?coal” residue can not be re-macerated separately to see its palynomorph content. Three supplementary samples of coal (928.95, 929.05, and 929.23 m) were obtained in March, 2000 after the original palynological analysis, to see if they might contribute to the resolution of the age of the sediment. These samples were scanned for useful taxa, which were recorded semi-quantitatively. (The floras were not age-diagnostic, with the exception of the presence at 929.23 m of *Diervilla* of McIntyre, 1991).

To yield maximum information, palynomorphs were identified and counted for all samples, except the supplementary coal samples. The palynomorph count target was 200 specimens, but the actual palynomorph sum varied with the abundance of palynomorphs in the sample. Data were recorded directly into StrataBugs, ver. 1.5, a paleontological database and plotting program. The data are provided in [Appendix 3](#).

The sequence of counting of the samples was determined by the initial focus of reporting on the gas hydrates hosting interval for G.S.C. Bulletin 544 (see Dallimore et al., 1999). First the cored interval from 886 to 952 m was counted and an interim report produced. Then counting began on the core from 111 to 118 m, and Dr. Martin Head (then, University of Toronto), was consulted on the dinoflagellate assemblages in that cored interval. Cutting samples from 670 to 1150 m were then counted, in a sequence from top to bottom.

After the initial report (White, 1999), a systematic review of the palynoflora was conducted from top to bottom of the well, including the 886 to 952 m cored interval. Rare taxa recorded from all samples were reviewed and about 120 digital images taken of significant or unknown taxa. For consistency in identification, taxa were checked against previous occurrences. Sample records were updated as re-analysis and image capture proceeded. Some samples have been reexamined four times. Taxonomic review of identifications has resulted in some changes. Two significant taxa, recorded in White (1999, Table 1) as *Mancicorpus* sp. of Ridgway et al.

1995 and as *Parviprojectus* sp. were combined in this manuscript and named *Striatocarpus sweetii*. Also, changes were made in identification of “unknowns”, recorded here as “Mallik2L-38 unknown_n” (see below).

Recycled Paleozoic and/or Mesozoic spores occur in most samples. Most of these could not be precisely identified but preservational features and/or diagenetic colour attributes allowed assignment to an unidentified Recycled Palynomorph category.

Norris’ taxonomy has been generally followed because much of the comparative data has been derived from the Adgo F-28 well, where Norris (1997) presents his latest palynostratigraphic zonation for the Cenozoic series in the Beaufort-Mackenzie Basin. The Adgo study was founded on previous work in the Nuktak C-22 well (Norris, 1986). Recently, Parsons and Norris (1999) and Parsons (2000) have made significant contributions in the analysis of the palynostratigraphy and taxonomy of the Reindeer Formation at the Caribou Hills. Parsons closely follows the taxonomy of Norris. Thus, the taxonomic usage of Norris, of Parsons, and of this study are compatible, excepting the use in this study of modern botanical names for taxa which can be referred to modern families/ genera/ species (White and Ager, 1994). To record unidentified palynomorphs in StrataBugs, a pseudo-genus/species designation is used here, i.e., “Mallik2L-38 unknown_n”. This designation permits unknown specimens to be attached uniquely to the Mallik 2L-38 well and a formal binomial can be proposed subsequently for an unknown, without affecting the identifications of taxa from other studies.

Where it was useful to make a specific comparison of a fungal palynomorph, this study generally follows the taxonomy of Norris (1986, 1997) and Elvik’s short course notes from (1981). Subsequently, Kalgutkar and Jansonius (2000) have comprehensively reviewed the taxonomy of fungal palynomorphs resulting in the transfer in this manuscript of *Diporisorites pisciculatus* Norris 1997 to *Inapertisorites pisciculatus* (Norris) Kalgutkar and Jansonius 2000.

Sums and Concentration Calculations

The palynomorph percentage diagram summation routines are designed to characterize the whole assemblage in terms of recycled, marine, and terrestrial (including lacustrine) components ([Table 1](#)). The percentages of these groups, and the individual taxa making them up are calculated as percentages of the Sum of Palynomorphs ([Figure 3](#)). Within this overall characterization of the assemblage, the Terrestrial Pollen and Spores are represented as a group ([Figure 4](#)), calculated as a percentage of the Sum of Terrestrial Pollen and Spores, to characterize the individual taxa and groups of taxa within the terrestrial component. The summation category into which each taxon was placed is in [Table 1](#).

<i>Osmunda regalis</i>	SP						1			
<i>Osmunda</i> sp.	SP						1			
<i>Osmundacidites wellmanii</i>	SP						1			
<i>Ostrya/Carpinus</i> undiff.	SP								1	1
<i>Ovoidites ligneolus</i>	SP			1						
<i>Paraalnipollenites alterniporus</i>	SP								1	
<i>Parviprojectus</i> A of Rouse 1977	SP								1	
<i>Picea</i> sp.	SP							1		
<i>Picea</i> sp. (robust corpus)	SP							1		
<i>Picea</i> sp. (small)	SP							1		
Pinaceae undiff.	SP							1		
<i>Pinus</i> (robust corpus)	SP							1		
<i>Pinus koraiensis</i> -type	SP							1		
<i>Pinus</i> sp.	SP							1		
<i>Pistillipollenites macgregorii</i>	SP								1	
cf. <i>Planera</i> sp.	SP								1	1
Poaceae undiff.	SP								1	
<i>Podocarpus</i> -type	SP							1		
Polypodiaceae/Dennstaedtiaceae	SP						1			
<i>Polyvestibulopollenites trinus</i>	SP								1	
<i>Pristinuspollenites microsaccus</i>	SP	1								
<i>Pristinuspollenites pannosus</i>	SP	1								
<i>Psilastephanocolpites</i> sp. cf. <i>P. marginatus</i> of Norris	SP								1	
<i>Pterocarya</i> sp.	SP								1	1
<i>Quercus</i> sp.	SP								1	1
Recycled palynomorphs	SP	1								
<i>Retimonocolpites excelsus</i>	SP	1								
<i>Retitricolpites</i> sp.	SP								1	
<i>Retitriteles</i> sp.	SP						1			
<i>Retitriteles</i> sp. cf. <i>R. novomexicanus</i> of Norris	SP						1			
<i>Rhoipites</i> sp. cf. <i>R. microreticulatus</i> of Norris	SP								1	
<i>Rhoipites</i> sp.	SP								1	
<i>Ribes</i> sp.	SP								1	
Rosaceae undiff.	SP								1	
<i>Rugubivesiculites</i> sp.	SP	1								
<i>Salix</i> sp.	SP								1	
<i>Schizosporis reticulatus</i>	SP			1						
<i>Sciadopitys</i> sp.	SP							1		
<i>Selaginella selaginoides</i>	SP						1			
<i>Shepherdia canadensis</i>	SP								1	
<i>Sparganium</i> sp.	SP								1	
<i>Sphagnum</i> sp.	SP					1				
<i>Stereisporites microgranulus</i>	SP					1				
Taxodiaceae-Cupressaceae-Taxa. undiff.	SP							1		
Tetrad pollen (scabrate)	SP								1	
Tetraporate spp.	SP								1	
<i>Tilia</i> -type	SP								1	1
<i>Tricolpites</i> sp.	SP								1	
<i>Tricolporopollenites</i> sp.	SP								1	
<i>Trilobosporites</i> sp.	SP	1								

<i>Tripartites incisotrilobus</i>	SP	1								
<i>Diervilla</i> of McIntyre (1991)	SP								1	
<i>Triporopollenites</i> sp.	SP								1	
<i>Trudopollis</i> sp., <i>T. ?barentsii</i>	SP								1	
<i>Tsuga canadensis</i> -type	SP							1		
<i>Tsuga heterophylla</i> -type	SP							1		
<i>Tsuga</i> sp.	SP							1		
<i>Tubuliflorae</i> undiff.	SP								1	
<i>Ulmus</i> -type	SP								1	1
Unknown and Undeterminable spp.	SP									
<i>Verrucatosporites favus</i>	SP						1			
<i>Vitreisporites pallidus</i>	SP	1								
<i>Wodehouseia spinata</i>	SP	1								
AC = acritarch										
AL = alga										
DC = dinoflagellate										
FU = fungus										
SP = spore or pollen										

Table 1: The summation category into which each taxon was placed is in.

The estimate of the concentration of palynomorphs/g of sediment is shown in [Figure 5](#). Such plots have high variability, so the data are presented in a logarithmic plot.

Criteria Proposed to Assess Recycling

It is difficult to prove that recycling has not affected fossil distributions, but this paper proposes that it is possible to assess the magnitude of the effect of recycling by analyses of the stratigraphic distributions of the palynomorphs. The criterion used to assess recycling is the coherence of the fossil distributions, and the environmental context of their occurrence.

In an idealized situation, if recycling were the dominant biostratigraphic signal, it would tend to create an inverted biostratigraphy as successively older rocks are unroofed and eroded. In a more realistic case, recycling would likely be episodic, and the recycled fossils derived from many different rock units. These recycled palynomorphs would be mixed with “contemporaneous” palynomorphs (i.e., palynomorphs which are a product of the ecosystem which existed contemporaneously with the deposition of the sediment), so intense recycling would likely produce a relatively chaotic distribution of palynological data. On the other hand, a primary biostratigraphic signal should show coherent distributions. Recycling is an unlikely explanation for a fossil’s occurrence if its distribution is comparable to other regional and extra-regional patterns, and evolutionary or environmental explanations, such as an appropriate match with other evidence of the paleoenvironment, can reasonably explain its occurrence. The coherence of the palynomorph distributions can be assessed by the concentrations and percentage distributions of common taxa, and by a non-parametric, statistical test of the distributions of rare taxa.

Randomness of distribution of rare taxa

White (1984) proposed that the randomness of distributions of rare taxa could be tested with the non-parametric Runs test (Siegel, 1956). As used here, runs are sequences of presence or absence of a particular taxon. The null hypothesis (H_0) of a test of runs is that the number of runs of presence and absence is within the limits that could be expected from a random draw from a population. The alternate hypothesis (H_1) is that fewer, or more, runs occur than would be expected by chance. Such distributions would suggest that some non-random factor is controlling the distribution. Biological and/or environmental forces are the most likely explanation for non-randomness.

Runs analyses were performed on Mallik 2L-38 palynological count data, excluding data from above 670 m because those data are not meaningful to the recognition of distribution patterns in the basal, problematic portion of the well. Forty taxa, which appeared to have some pattern of clustering in their distributions, were analysed by the Wald-Wolfowitz Runs Test using the statistical package Systat 5.02 for Windows. The H_0 for each of the selected taxa is that the distribution of presences and absences is not different from a random pattern. The raw abundance record of rare taxa is commonly 1 or 0, so 0.5 was chosen as a discriminator to separate the taxa into runs. As the sample is large (73 stratigraphic levels), the sampling distribution for r is approximated by a normal distribution (Siegel, 1956).

Results and Interpretation

Overview

A total of 16108 palynomorphs and some 220 taxa were identified and tallied during the palynological analysis [count per sample: \bar{x} = 194.07, s = 73.96, minimum 19 (at 720 m), maximum 299 (at 1120 m)]. In the core no. 12 to no. 24 interval, palynomorph sums range from 63 to 316 specimens per sample.

The interpretation of the palynological results is best done in two separate blocks because there is about 550 m of non-recovery of samples between the cores 1 and 2 (samples 111.12 to 118.34 m) and the top of the cutting record at 670 m. Cores 1 and 2 provide a small sample of upper Neogene strata, not normally recovered by industrial drilling in the Mackenzie Delta. It is important to report these data, but they are not germane to the main question of the age of the strata between 670 and 1150 m.

The focus of this paper and following discussion is on the strata penetrated by the well between 670 to 1150 m. As discussed above, identification of the ages of rocks and sequences penetrated by the Mallik 2L-38 well is contentious. This disagreement between continental and marine biostratigraphic results is a useful opportunity to consider and clarify the differences, to the benefit of biostratigraphy, and to the interpretation of regional geology. The following discussion: 1) describes the palynological results from the Mallik 2L-38 well, and demonstrates that patterns exist which argue against recycling as the primary signal in the palynological record; 2) considers correlation and age assignment for several intervals, necessitating a consideration of

the taxonomy of some triprojectate pollen found in northern Paleogene rocks, of correlation options to other surface and subsurface sections, and a consideration of age the constraints of the foraminiferal *Haplophragmoides richardsensis* zone and the *H. richardsensis* zone in the Mallik L-38 well; 3) considers existing paleoclimatic evidence for the Eocene-Oligocene boundary and derives paleoclimatic interpretations from palynological count data from Mallik 2L-38; 4) uses the paleoclimatic results to compare with the North Atlantic $\delta^{18}\text{O}$ paleoclimatic record to refine the age interpretation, and 5) compares the interpretations to regional tectonic patterns.

Palynology, Correlation and Age in the 111 to 670 m Interval

110.11 - 118.35 m, Late Pliocene - Pleistocene

[Figure 4c](#) shows the distribution of palynomorphs in samples from samples 111.12 to 118.34 m in Cores 1 and 2. Cyperaceae, *Artemisia*, Tubuliflorae and Poaceae occur commonly in this interval. The former three do not occur lower in the well, and the latter does not occur below 690 m. *Sphagnum* is more abundant than in the underlying intervals. Total gymnosperms are also more abundant, made up chiefly of *Picea* and secondarily *Pinus*.

Artemisia, Tubuliflorae, Poaceae and Cyperaceae suggest a correlation to the Poaceae Zone of White et al. (1999). Although all of these taxa may range downwards into the Miocene, they do not become common at high latitude until the Pliocene and Pleistocene. A maximum Pliocene age is supported by the paucity of *Tsuga*, which is common in the Miocene (White et al., 1999).

Artemisia, present but not abundant in this interval, argues for an age in the Late Pliocene to Pleistocene (White et al., 1999). On the other hand, the abundance of Taxodiaceae-Cupressaceae-Taxaceae (T-C-T) pollen in this interval ([Figure 4a](#)) suggests an older, Pliocene age, probably the middle Pliocene warm interval (Dowsett et al., 1994; White et al., 1999). Inasmuch as there is abundant Cretaceous recycling in this interval ([Figure 6](#)), and T-C-T pollen is abundant in Cretaceous and Paleogene rocks, recycled specimens could have contributed to the T-C-T sum. Thus, it seems best to give more weight to the presence of *Artemisia*. A study of the adjacent Mallik 5L-38 well argues that evidence of glaciation occurs between 340 and 270 m. Significant Northern Hemisphere glaciation began about 2.75 Ma (Shackleton et al., 1984; Kleiven et al., 2002), so this interval is probably of Late Pliocene to Pleistocene age.

The dinoflagellate *Habibacysta tectata* Head et al. 1989 was questionably identified in the uppermost sample 110.11 m. This taxon has a stratigraphic range from the middle Miocene to lower upper Pleistocene at high northern latitude (Head et al., 1989). Although it does not refine the age interpretation for the sample, its presence would argue for a marine influence in the sample. Several other unidentified dinoflagellate specimens were included in the “Dinoflagellate indetermined” category, although it is possible that they have been recycled from older strata.

The great abundance of recycled palynomorphs in cores 1 and 2 ([Figure 3](#)) is a response to increased erosion and sedimentation rates in the Pliocene and Pleistocene, which may be due to

increased climatic oscillation (Peizhen et al., 2001), or to regional tectonic activity.

118-670 m, unknown

Drilling problems resulted in considerable caving in intervals above 677 m, the depth at which surface casing was set (Ohara et al., 1999). There are only two short core increments between 118 m and 680 m, and neither yielded palynomorphs. This long interval with no biostratigraphic information consequently provides no constraints to assist in the interpretation of older events.

Palynological Results and the evaluation of recycling in the 670 to 1150 m interval

The following discussion argues that palynological data from Mallik 2L-38 shows biological patterning, evident both by inspection of the percentages of dominant taxa, and by statistical analysis of the distributions of rare taxa. It is argued that, although there are clearly recycled palynomorphs in this palynological record, the effect of recycling does not vitiate the primary biostratigraphic evidence.

Concentration Estimates of Palynomorphs

A simple measure of the coherence of distribution of organic matter in the sediment is the concentration of palynomorphs per gram of sediment. This measure reflects both the rate of palynomorph supply through organic productivity, and the rate at which palynomorphs are diluted in the sediment (the sedimentation rate). It does not demonstrate which palynomorphs are recycled and which are not, but it does offer a simple assessment of patterns in organic matter distribution. This technique had not been used previously in Beaufort-Mackenzie region biostratigraphic palynology so it can not be compared against other data.

[Figure 5](#) shows an estimate of the concentration of palynomorphs per gram of sediment, derived by using the independent counts of the exotic marker and the fossil pollen. The plot is not scaled to depth so that the data points from the closely spaced samples in the cored interval can be individually resolved. The sample from which the sample weight and exotic marker tablet number were estimated (see above) are shown by triangles, and other samples are shown by diamonds. The same *Lycopodium* tablet batch was used throughout the well, and the sample processing batches of 16 samples do not coincide with major concentration changes, ruling out laboratory processing as possible explanations of the major changes in the concentration values.

Three patterns are immediately apparent ([Figure 5](#)). In the intervals where the data were derived from core samples there is much higher variability than in the intervals where data were derived from cuttings. This high variability in pollen concentration and influx measurements is typical of palynological results from late Quaternary sediments (e.g., White and Mathewes, 1986), in which palynological samples are taken of very short sediment increments. The averaging effect of samples taken over 10 m increments, rather than 2 cm increments, likely explains the lower concentration variability of the cutting samples. Another obvious pattern is that the concentration of palynomorphs per gram in the core samples is about an order of magnitude higher than in the

cutting samples. This is due to the acquisition of core samples only from organic-rich intervals. It is also apparent that the samples from the lower cutting interval (1150 to 960 m) have a concentration some three or four times higher than the samples from the upper cutting interval (880 to 670 m). This consistent pattern must be due to fundamental differences in biological productivity or sedimentation rate, or both.

The difference in concentration estimates between the upper and lower cutting intervals is a gross measure, but is evidence that there are distinct patterns in the palynological signal through the depth of the well. This argues against a chaotic pattern of palynomorph deposition.

Patterns of Terrestrial Pollen and Spore Assemblages

[Figure 4a](#) shows, for the whole well, the percentages of individual taxa of terrestrial pollen and spores, and totals for the groups; fungi, bryophytes, ferns and fern allies, gymnosperms and angiosperms. [Figure 4b](#) shows the percentages of Terrestrial Pollen and Spores for the 886 to 952 m cored interval, which can not be shown clearly on the [Figure 4a](#) because the samples are at much closer intervals than for the rest of the well. Percentages are based on the Sum of Terrestrial Pollen and Spores in order to represent changes happening within the terrestrial plant community.

Pollen Percentages in Core vs. Cuttings

[Figure 4a](#) shows that there is a significant increase in Taxodiaceae-Cupressaceae-Taxaceae (T-C-T) percentage abundance and a decline amongst the Pinaceae across the transition from the uppermost core sample at 886.38 to the overlying cutting sample at 880 m.

Do percentage changes near 886 m reflect regional ecological changes, or are they due to the change from core to cuttings samples? The most distinctive Pinaceae percentage changes are declines in *Pinus* and *Picea*. The concomitant decline in “Pinaceae undifferentiated” indicates that this was not a change in the preservation of *Pinus* and *Picea* from core to cuttings. An apparently coeval *Larix/Pseudotsuga* percentage decline is actually at 891.1m, two samples below the core/cutting transition. The validity of the upper core-to-cutting percentage change can also be assessed by comparison with the lower transition from cuttings at 960 m to core at 951.3 m. This lower transition shows no abrupt percentage effect, and palynomorph percentage changes are consistent with longer-term trends. This argues that the core-to-cutting transition is not the factor that affects percentages of T-C-T, *Pinus*, *Picea* and Pinaceae undifferentiated.

The likely explanation for the percentage change at the top of the core is that it represents some vegetation change associated with climatic or sedimentological change at the top of the core, an interpretation supported by the palynomorph concentration estimates ([Figure 5](#)). This may bear on the gas hydrate host properties of the rock and help explain the accumulation of gas hydrates below 886 m. Lithological descriptions across the core-to-cutting transition do not resolve such changes, but spectroscopic gamma ray values above 886 m show a drop in average values and a reduction in oscillations (Collett et al., 1999b) although changes of equivalent significance are seen elsewhere in the well.

General Features of Percentage Distributions

[Figure 4](#) shows all of the information about the percentages of palynomorphs in this study. It is useful to draw the readers attention to the broad features, and some of the critical details, of these data. This shows the coherence of the patterns in the percentages, and some features may be referred to in subsequent discussion. It also show that the distributions of dominant and rarer taxa are not chaotic, but strongly patterned with consistent, long-term trends, thus arguing against recycling as a dominant factor governing palynomorph distributions.

Interpretational significance is attached to general trends in occurrence, spanning several samples, rather than to high or low abundance patterns defined by only single samples. Trends shown by several samples in sequence are considered to represent long-term biological events with evolutionary or paleoenvironmental/paleoclimatic significance. Variations of individual samples may represent a local niche effect or short-term (< 1 ky) climatic variation on the sample assemblage. Some patterns can be attributed to inconsistencies in the analysis, and these are pointed out. Not all taxa are discussed below, rather only those that have patterns in their distributions which bear on the stratigraphic integrity of the palynological evidence, on the biostratigraphic, paleoecologic, and paleoclimatic interpretations, or on the analysis.

Patterns of change of percentage abundance can be readily detected by inspection of numerically dominant taxa. Although stratigraphic patterns of occurrence may be present in numerically rare taxa they are difficult to evaluate by visual inspection, and require statistical analysis. The following discussion focuses on the dominant taxa. Rare and biostratigraphically significant taxa are treated in the discussion of a statistical test of runs (below).

Fungi

Fungal remains occur consistently between 1150 and 670 m but are never abundant ([Figure 4](#)). The increased abundances of the long, filamentous *Fractisporonites* sp. and fungal hyphae in the cored interval are probably due to better preservation of the fossils in the fine-grained, organic-rich samples from core.

Ferns and fern allies

Laevigatosporites sp. and *Deltoidospora* sp. have higher abundance below 928 m than above ([Figure 4](#)). This transition occurs across the 926.5 m sequence boundary proposed by Jenner et al (1999). The core-to-cutting change has no effect on the *Laevigatosporites* percentages.

The gap in occurrence of *Baculatisporites crassiprimarius* in the cored interval is because it was counted as a recycled palynomorph during the first phase of core analysis. When cuttings were analysed, the validity of that interpretation was questioned, and *B. crassiprimarius* was recognized and tallied separately.

Gymnosperms

Picea has a peak in percentages near 893 m, and generally greater abundance above the cored interval than below it.

T-C-T is an abundant taxon. The increase across the core-cutting transition about 880 m is part of a long term trend, declining in percentage from TD to about 960 m, and then increasing to 740 m, and subsequent decline. From 880 to 670 m the T-C-T percentages are more variable than in underlying strata.

T-C-T pollen are both abundant and long-ranging at high latitude, occurring from the Cretaceous to the late Neogene, and could be readily recycled from older strata. To assess potential recycling, [Figure 6](#) shows a plot of T-C-T and Total Recycled Palynomorphs, both calculated as percentages of the Sum of Palynomorphs. [Figure 6](#) is unscaled to depth so that points in the core interval are not vertically compressed. There is no similarity in percentage pattern of these curves, arguing that the T-C-T category is not dominated by pollen recycled from Cretaceous strata.

Pinus sp. is abundant and shows two episodes of peak abundance. The first rise in abundance begins at 960 m, with high values through the core, and a decline starting at 893.18. The next episode of increase starts at 720 m.

Tsuga spp. have been subdivided into *-canadensis* type and *-heterophylla* type, using the absence or presence of micro-echinae on the vellum (White and Ager, 1994). *Tsuga* spp. was used for those specimens which were not well enough preserved for separation into types. *Tsuga heterophylla* -type shows a small peak centred at 960 m. *T. canadensis* -type shows a general pattern of increase above 951.29 m, where it is generally more abundant than in underlying strata. Within the cored interval, *T. canadensis* -type has a distinct bimodal distribution, separated by a unique absence of *Tsuga* spp. at 944.32 m (see discussion of *Ephedra*, below).

An occurrence of *Ephedra* at 944.32 m, with an uncommon absence of *Tsuga* spp. was interpreted by White (1999) as evidence of edaphic dryness, as *Ephedra* taxon has been observed in brackish water to marine deposits in the Lower Tertiary of Europe and North America. *Ephedra* may have been both a xerophyte and a halophyte, which could occupy dunes and beaches, as well as other pioneering habitats (Frederiksen, 1985). It may not be coincidental that this *Ephedra* occurrence is adjacent to the 945.2 to 948.1 m interval where which Kurita and Uchida (1999) observed Paleogene dinoflagellates. During the subsequent review of samples, *Ephedra* sp. was also found at 936.32 m, but there occurring with *Tsuga* spp. This does not invalidate the above interpretation, because edaphically dry habitats, suitable for *Ephedra*, may have existed adjacent to more mesic to humid habitats, suitable for *Tsuga*.

Angiosperms

Patterns in *Alnus* pore numbers are readily observed during analysis, although the taxonomic or ecological significance of pore numbers is unclear. Nonetheless, the continuity of these patterns can serve as a simple tool to assess and stratigraphic integrity of the section. *Alnus* sp. is divided into three morphotypes of 4 to 6 pores. An interval of increased *Alnus* 4-porate abundance spans 946.21 m to 770 m. Notably, this pattern is not affected by the core-to-cutting transition. Both 5- and 6-pore *Alnus* percentages show intermittent and apparently asynchronous

fluctuations.

The separation and interpretation of triporate pollen is problematic, because it relies on subtle features of the amb profile and internal features of the aperture. The range of variation of various taxa results in morphological overlap, and many specimens can only be categorized as *Triporopollenites* sp. Most triporate taxa have affinities with the modern Betulaceae or Myricaceae (*Betula*, *Carpinus*, *Comptonia*, *Corylus*, *Myrica*) but this is complicated in the Paleogene by the *Momipites* lineage, affiliated with the Juglandaceae (Nichols, 1973). *Betula* sp. was divided into small and larger morphotypes (\leq or $> 20 \mu\text{m}$). The larger is more common, and shows a pattern of increased abundance beginning in the upper cored interval at 903.82 m, and continuing to 670 m, with general bimodality. Both *Betula* and *Triporopollenites* show highest abundance within the cored interval, and generally greater abundance above 1000 m than below. The absence of *Momipites wyomingensis*? between 886 and 952 m is evidently a result of this species having been counted as *Corylus* -type pollen during the first analysis phase.

Ericales (White and Ager, 1994) are generally more abundant below the cored interval than above ([Figure 4a](#)). A peak and drop in abundance across 1000 m may suggest a lithological boundary. A peak occurs at 928.81 m, and between 830 and 670 m, two minor peaks occur. The interval of 890.7 to 840 is a period of reduced abundance or absence of Ericales.

Magnolia sp. pollen first appears at 950.11 m just above the base of core, with a gradual percentage rise over 7 samples to 944.32m. ([Figure 4b](#)). This pattern suggests a real first appearance in Mallik 2L-38, as opposed to a cutting/core effect. It occurs commonly but not abundantly up to 670 m.

Pterocarya sp. is a slightly more abundant, and has a more regular pattern of occurrence below 990 m than above. Between 886.4 and 840 m it occurs only in one sample.

Tilia -type pollen (White and Ager, 1994) is rare, and does not occur above 850 m.

Ulmus -type pollen (White and Ager, 1994), has a bimodal distribution within the cored interval. Below the cored interval it has a bimodal occurrence, formed by an interval of reduced abundance about 1050 m. Above the core, it occurs consistently, except for an absence between 720 and 760 m.

Recycled, Dinoflagellates, Algae and Undeterminable Categories

[Figure 7](#) illustrates the relative abundance of palynomorphs in three categories, recycled palynomorphs, dinoflagellates and algae. The percentages of all taxa in this diagram are calculated on the Sum of all Palynomorphs, representing their abundance as a percentage of the whole assemblage.

“Recycled Palynomorphs” includes those that can be determined to species, and a category of undetermined recycled palynomorphs. This latter category includes taxa which are badly preserved and not clearly identifiable, but are most likely recycled. Discretely identifiable

recycled specimens are relatively rare compared to the undetermined specimens. The Recycled Palynomorphs abundance is high between 110 and 118 m, indicating a time of active erosion, and conversely Recycled Palynomorphs are very rare below 1010 m. Otherwise, Recycled Palynomorphs are generally less than 5 % of the assemblage.

The identified recycled palynomorphs indicate the recycling of older rocks into strata penetrated by the Mallik 2L-38 well. *Aquilapollenites* spp. and *Chatangiella ditissima* (McIntyre) Lentin and Williams 1976, indicate recycling from Santonian to Maastrichtian strata (Lentin and Williams, 1993; Nichols and Sweet, 1993). *Wodehouseia spinata* Stanley 1961 is indicative of recycling from the late Maastrichtian to the earliest Paleocene (Nichols and Sweet, 1993). *Cicatricosisporites* spp., *Gleicheniidites senonicus* Ross 1949, *Pristinuspollenites* spp., *Rugubivesiculites* sp., *Trilobosporites* sp. and *Vitreisporites pallidus* (Reisinger) Nilsson 1958 indicate recycling from Early to mid- Cretaceous rocks (Burden and Hills, 1989). *Densosporites rarispinosus* Playford 1963 is recycled from Lower Carboniferous rocks (J. Utting, pers. comm., 3 March 2000). There is little clustering in the distribution of identifiable recycled taxa, but there is a small cluster of Cretaceous taxa in the 948.16 to 937.36 m interval.

Undeterminable palynomorphs, which are either too corroded or obscured to put in any category, generally make up less than 12% of all palynomorphs, excepting an abundance peak of 23% at 935.78 m. The great abundance of these taxa in cores 1 and 2 is notable.

Runs Test of the Distribution of Rare Taxa

[Table 2](#) shows the results of the runs test of the significance of distribution of rare taxa. The results are sorted from low to high probabilities. Thirteen taxa, from "Mallik2L-38 unknown 06" to *Striadiporites inflexis* have probabilities associated with their distributions of less than 0.01. Taxa from *Aceripollenites tener* to *Magnolia* sp. have probabilities less than 0.5. and *Striatocarpus sweetii* and *Tilia*-type have associated probabilities less than 0.1. Thus, we may conclude that 18 taxa show patterns of distribution which are extremely to somewhat unlikely to be caused by random chance, and we may credibly reject the H_0 for those taxa. The negative z scores indicate fewer runs than would be expected by random chance, i.e., that some other factor, likely biological or environmental, is influencing the distribution.

It can be justifiably argued that the greater intensity of sampling in core vs. cuttings results in a greater probability of runs of presences occurring in the core interval, and absences in the cuttings. To assess this problem, the taxa are coded as to whether they occur in core, cutting, or in both. Of the taxa with low probability distributions, eight occur only in the cutting samples, spread over various stratigraphic levels, i.e., *Foveosporites* sp., Mallik2L-38 unknown 06, *Retritiletes* sp. cf. *R. novomexicanus* of Norris, *Nyssa* sp., *Verrucatosporites favus*, *Striadiporites inflexus*, *Stereisporites microgranulus*, and *Striatocarpus sweetii*. Three taxa occur exclusively in the core interval, i.e., Mallik2L-38 unknown 25, *Ovoidites lignoleus*, and *Podocarpus*-type. Seven taxa occur in core and cuttings, i.e., *Quercus* sp., *Lonicera pollis gallwitzii*, *Fagus* sp., *Labrapollis* sp., *Aceripollentia tener*, *Magnolia* sp. and *Tilia* -type.

Inspection of [Figure 4a](#) shows that these statistically non-randomly distributed rare taxa are found occurring throughout the 670 to 1150 m interval, suggesting that non-random pattern of occurrences are not determined by clustering factors associated with any specific part of the sequence. In other words, there is no specific part of the 670 to 1150 m interval which shows patterned occurrences, while other parts show random occurrence. Various taxa have stratigraphic occurrence patterns which are apparently biologically driven, and which occur throughout the 670 to 1150 m interval. If the proposed criterion of a non-random pattern of occurrence assists in separating palynomorph occurrences showing biological patterns versus one dominated by recycled palynomorphs, the patterned occurrences, shown above, argue against recycling as a useful explanation of palynomorph distributions in the Mallik 2L-38, 670 to 1150 m interval.

Comparison of the scores with [Figure 4a](#) shows that the test of runs is particularly sensitive to contiguous occurrences of the selected taxa. However, other taxa amongst the original 38 chosen, have some distinct patterns of clustering to which a test of runs is not sensitive. A long interval of absence of a taxon (eg. in *Cicatricosisporites paradorogensis*) constitutes just one run, although that pattern of presence and absence intuitively appears significant, this is not resolved by the runs test.

Case s < cut	Case s > cut	R un s	Z	Probability (2-tailed)	Palynomorph
71	2	3	-4.783	<0.001	Mallik2L-38 unknown 06 ■
71	2	3	-4.783	<0.001	Mallik2L-38 unknown 25 •
69	4	5	-4.29	<0.001	<i>Ovoidites ligneolus</i> •
67	6	7	-4.051	<0.001	<i>Podocarpus</i> -type •
61	12	12	-3.93	<0.001	<i>Quercus</i> sp. ■•
61	12	8	-5.667	<0.001	<i>Retitriteles</i> sp. cf. <i>R. novomexicanus</i> of Norris ■
67	6	8	-3.243	0.001	<i>Lonicera pollis gallwitzii</i> ■•
66	7	9	-3.253	0.001	<i>Nyssa</i> sp. ■
66	7	9	-3.253	0.001	<i>Verrucatosporites favus</i> ■
63	10	12	-3.171	0.002	<i>Fagus</i> sp. ■•
63	10	12	-3.171	0.002	<i>Labrapollis</i> sp. ■•
70	3	5	-2.845	0.004	<i>Foveosporites</i> sp. ■
70	3	5	-2.845	0.004	<i>Striadiporites inflexus</i> ■

67	6	9	-2.435	0.015	<i>Aceripollenites tener</i> ■•
67	6	9	-2.435	0.015	<i>Stereisporites microgranulus</i> ■
50	23	25	-2.055	0.04	<i>Magnolia</i> sp. ■•
69	4	7	-1.881	0.06	<i>Striatocarpus sweetii</i> ■
61	12	17	-1.76	0.078	<i>Tilia</i> -type ■•
59	14	20	-1.392	0.164	<i>Tsuga heterophylla</i> -type ■•
70	3	6	-1.222	0.222	<i>Liquidambar</i> sp. ■
66	7	12	-1.158	0.247	<i>Paraalnipollenites alterniporus</i> ■•
65	8	17	1.083	0.279	<i>Jussiaeae (Ludwigia)</i> sp. ■•
61	12	23	0.844	0.398	<i>Carya</i> sp. ■•
68	5	11	0.66	0.509	<i>Castanea</i> -type ■•
68	5	11	0.66	0.509	<i>Juglans</i> sp. ■
60	13	21	-0.557	0.577	Mallik2L-38 unknown 12 ■•
69	4	9	0.528	0.597	Apiaceae ■•
69	4	9	0.528	0.597	<i>Ilex</i> -type •
69	4	9	0.528	0.597	<i>Rhoipites</i> cf. <i>microreticulatus</i> of Norris 1997 ■
70	3	7	0.4	0.689	<i>Cicatricosisporites paradorogensis</i> ■
70	3	7	0.4	0.689	<i>Integricarpus</i> sp. A of Norris 1986 •
71	2	5	0.277	0.782	Mallik2L-38 unknown 09 ■•
71	2	5	0.277	0.782	Mallik2L-38 unknown 19 ■•
71	2	5	0.277	0.782	<i>Psilastephanocolpites</i> cf. <i>marginatus</i> of Norris 1997 ■
72	1	3	0.168	0.867	<i>Boisduvalia clavatites</i> •
72	1	3	0.168	0.867	<i>Diervilla echinata</i> ■
72	1	3	0.168	0.867	<i>Parviprojectus</i> A of Rouse 1977 •
72	1	3	0.168	0.867	<i>Pistillipollenites macgregorii</i> ■

Table 2. Wald-Wolfowitz test of randomness of occurrence of rare taxa, calculated by Systat

5.02. The occurrence pattern of the rare taxa is commonly 1 or 0, so 0.5 was chosen as a discriminator (cut) to separate the taxa into runs. The H_0 is that the occurrences of presences and absences shown by each of the selected taxa is not different from a random pattern. The negative z scores indicate fewer runs than would be expected by random chance (■ - occurs in cuttings, • - occurs in core).

Balance of Evidence Regarding Recycling

It has been demonstrated that there are strongly patterned distributions of palynomorphs in Mallik 2L-38, both on common taxa and in rare taxa. This is taken to show that the palynological analysis of Mallik 2L-38 yields a primary biostratigraphic signal amenable to age and environmental interpretation. Nonetheless, these considerations assess the “balance of evidence” regarding recycling, and do not produce a definitive answer for any particular taxon. The following interpretation is based on the assumption that palynomorphs are largely in place.

Correlation and Age

Several factors impinge on biostratigraphic correlations. Biostratigraphic indicators are relatively rare taxa, and a detailed knowledge of their stratigraphic ranges requires many individual studies. The ecological tolerances of fossil plants, although poorly known, influence presence or absence events. Sedimentary sequences, especially fluvial sequences, contain many disconformities that may mask the true stratigraphic ranges of taxa. Northern Cenozoic palynostratigraphy has advanced well beyond initial exploration, but falls short of firmly established zonations. Nonetheless, biostratigraphers must select taxa that are morphologically distinctive and about which they judge there to be a reasonable level of stratigraphic knowledge. Even for well known taxa, range extensions will typically be observed as a greater sample size expands knowledge of any taxon's distribution.

670-860 m, ?Early Miocene - ?Oligocene

In the interval 670-775 m, thermophilous hardwoods occur rarely; a questionable *Fagus* at 680 m, *Carya* at 690 m and *Castanea* -type pollen at 730 m. These taxa argue for an age older than 6 Ma, and most likely older than 12 Ma (White et al., 1999). Onshore, the Middle Miocene warm interval (ca. 15 Ma) has a rich thermophilous assemblage, although it is represented more tenuously offshore, in Issungnak O-61 (White, 1989; White and Ager, 1994; White et al., 1999). In Mallik 2L-38, this rich assemblage is absent; hence it is unlikely that the Middle Miocene warm interval is represented in the samples analysed. However, the paleoclimatic interpretation, presented below would suggest that this is an Oligocene to ?early Miocene interval.

As the age constraints for the 670 - 775 m interval are not definitive, the same possibilities must be considered for the 775 - 860 m interval. Within the Neogene, *Liquidambar* has been proposed as a Middle Miocene indicator (White et al., 1999). *Liquidambar* occurs at 830 m in

Mallik 2L-38, but it also does not co-occur with the rich assemblage of thermophilous angiosperms typical of the warm interval (White and Ager, 1994; White et al., 1999). *Tilia* -type underlies *Liquidambar* at 860 and 850 m, and *Ilex* -type, *Castanea* -type and *Fagus* occur above *Liquidambar*, between 800 and 780 m. A Middle Miocene age also seems unlikely for this interval, even though the dispersed distribution of thermophilous taxa might be due to the relatively low palynomorph sums (54 - 110 grains per sample) in the stratigraphic interval from 800 to 850 m.

An alternative age interpretation derives from Whitlock and Dawson's (1990) report of single grains of *Juglans*, *Carya*, *Acer*, *Ilex* and *Liquidambar* at the top of the type section of Haughton Formation, within the Haughton Astrobleme on Devon Island. The sparsity of these thermophilous pollen types suggests that they were deposited by airborne, long-distance transport from the south. Whitlock and Dawson (1990) concurred with Hickey et al. (1988) that the Haughton Formation was deposited within the Aquitanian Age (23.8-22.3 Ma, Cande and Kent 1992, 1995). The age of impact is limited by radiometric determinations and the upper age of the crater fill is determined from field relationships. A short-lived marine $\delta^{18}\text{O}$ excursion in the earliest Miocene (Pearson and Palmer, 2000) suggests temperatures approaching those of the Middle Miocene climatic optimum. Thus sediment infilling the Haughton Astrobleme may have recorded an Early Miocene warm interval.

The late Oligocene also had an episode of warm climate (Miller et al, 1987; see discussion below), but the associated palynomorph assemblages are not known from outcrop in northern Canada. Thus 775 - 860 m interval may represent an as-yet poorly known biostratigraphic/ warm climatic event(s) in the Oligocene to earliest Miocene interval.

860 m - 926.5 m, Oligocene

Following arguments presented below, the Eocene - Oligocene boundary is considered to be at the disconformity at 926.5 m, and consequently the sediment overlying to be of Oligocene age. The early Oligocene cold interval is thought to be represented in sediment around 897 m, adjacent to the top of the gas hydrate hosting interval. Overlying sediment to 860 m, or above, is thought to be of Oligocene age.

926.5 m - 1150 m, Late Eocene

In Mallik 2L-38, Jenner et al. (1999) place the lower boundary of the Mackenzie Bay Sequence at the base of a dolomite cemented sandstone at 926.5 m, which forms a sharp or erosional contact with the underlying strata. This is a boundary between a lower deltaic plain, marsh to shallow marine environment, and an overlying fluvial environment. Jenner et al. (1999) consider this to be an abrupt boundary between the underlying Kugmallit Sequence and overlying Mackenzie Bay Sequence. This study adopts Jenner's boundary at 926.5 m as a significant chronological break, but proposes a different chronological interpretation.

The correlation and determination of the age of Mallik 2L-38 strata from 926.5 to 1150 m is considered under six topics:

1. A consideration of the age and environment of deposition of dinoflagellates identified by Kurita

and Uchida (1999) in core samples from 926.2 and 948.1 m.

2. A discussion of the taxonomy of the triprojectate pollen *Integricorpus* and *Parviprojectus*, which are important for correlation in the Paleogene.
3. Discussion of possible correlations between Mallik 2L-38 and the Caribou Hills section.
4. Correlation of Mallik 2L-38 to Adgo F-28 by Last Appearance Datums (LADS).
5. Consideration of the biostratigraphic ranges of indicators found in Mallik 2L-38 but not in the Caribou Hills sections nor in Paleogene-early Neogene sections of Adgo F-28 or Nuktak C-22 wells.
6. Identification of a possible disconformity within this sedimentary interval at 1000 m.

Dinoflagellates from 945.21 and 948.16 m

Kurita and Uchida (1999) identified dinoflagellates of Paleocene-Eocene age in samples from 945.21 and 948.16 m, but concluded that they must be recycled if, "... the deepest part of the section is correlated with the Oligocene Kugmallit Sequence, as indicated by Dallimore et al. (1999) and Jenner et al. (1999)...". They considered their assemblage similar to that reported from the Taglu Sequence of the western Beaufort (Dietrich et al., 1989), comprising 20 taxa. Another assemblage of Taglu Sequence dinoflagellates from the Caribou Hills, south of Mallik 2L-38, comprising some 64 taxa, has been reported in detail by Parsons (2000). The critical question is whether the Kurita and Uchida's Mallik assemblage is similar enough to the Taglu assemblage to constitute definitive evidence of recycling.

[Table 3](#) compares the occurrence of dinoflagellates identified by Kurita and Uchida (1999) in Mallik 2L-38 with occurrences in the Taglu Sequence of Natserk E-56 well (Dietrich et al., 1989) and the Caribou Hills (Parsons, 2000). The chronostratigraphic ranges of the taxa is drawn from syntheses by Williams et al. (1993, 1998). Williams et al. (1993) use the timescale of Haq et al. (1987).

Mallik 2L-38 taxa (Kurita and Uchida, 1999)	Taglu Sequence, Natserk E-56, (Dietrich et al., 1989)	Taglu Sequence, Caribou Hills (Parsons, 2000)	Chronostratigraphic range (Williams et al., 1993 or Williams et al. 1998)
<i>Apectodinium homomorphum</i>	<i>Apectodinium homomorphum</i>	<i>Apectodinium homomorphum</i>	Early to Middle Eocene (55-41 Ma)
<i>Cordosphaeridium fibrospinosum</i>			Cretaceous to Early Oligocene (33 Ma)
<i>Deflandrea</i> sp. ind.	contains a <i>Deflandrea</i>	Deflandreoid dinoflagellates	late Early Cretaceous to Neogene
<i>Glaphyrocysta divaricata</i>	<i>Galphyrocysta divaricata</i>	<i>Glaphyrocysta divaricata/pastelsii</i>	Early Eocene
<i>Glaphyrocysta exubarens</i>			Early to Late Eocene (54-38 Ma)

<i>Hystrihokolpoma?</i> sp.		<i>Hystrihokolpoma</i> <i>reticulatum</i> and species	Late Cretaceous to Neogene
<i>Lentinia serrata</i>			late Middle to Late Eocene (43-37 Ma)
<i>Spiniferites</i> sp. cf. <i>pseudofurcatus</i>		<i>Spiniferites</i> spp.	Cretaceous to Late Miocene (10.2 Ma)

Table 3. Comparison of the occurrences of dinoflagellates reported by Kurita and Uchida (1999) from Mallik 2L-38, 945.21 and 948.16 m, with dinoflagellates from the reported from the Taglu Sequence by Dietrich et al. (1989) and Parsons (2000), and with their reported chronostratigraphic ranges (Williams et al., 1993, 1998).

At a species level, only two of the eight Mallik dinoflagellates, *Apectodinium homomorphum* and *Glaphyrocysta divaricata*, are shared with both the assemblages of dinoflagellates reported from the west Beaufort and from the Caribou Hills. The currently known stratigraphic ranges of both *Apectodinium homomorphum* and *Glaphyrocysta divaricata* argue for recycling from Early to Middle Eocene rocks. On the contrary, the Mallik taxon, *Lentinia serrata* occurs in neither Taglu Sequence assemblage, and has a fairly restricted range in the late Middle to Late Eocene. Thus, on close examination, the evidence of recycling from the dinoflagellates is questionable.

The Mallik dinoflagellates reported by Kurita and Uchida (1999) are found in a section of the core that Jenner et al. (1999) described as being moderately organic-rich, clayey silt and low rank coal with sandy burrow fills, interpreted to represent “relatively quiescent marine deposition”. Not only is this an unlikely environment to find recycling, but it is an environment in which dinoflagellates would reasonably be expected to occur. These dinoflagellates were not observed in fluvial sediment above 926.5 m, where recycling would be more expected.

Some insight to the ecological tolerances of these dinoflagellates, based on tolerances of modern relatives, is found in Powell et al.’s (1996) study of Upper Pleocene - Lower Eocene dinoflagellates. The *Apectodinium* complex is highly tolerant. The *Cordosphaeridium* and *Spiniferites* complexes represents open marine, neritic water masses, and the *Glaphyrocysta* group, inner neritic water masses. The *Deflandrea* complex are probably heterotrophs, associated with high nutrients such as upwelling areas and river mouths. Thus, the Mallik assemblage is not inconsistent with a nearshore environment, highly influenced by terrestrial organic matter, such as represented by the bioturbated mudstone in this portion of the Mallik 2L-38 well.

The Integrator/ Parviprojectus question

The triprojectate pollen *Integrator* sp. A has figured prominently in correlations proposed by Norris (1986, 1997) as the nominate species for a palynostratigraphic zone. The

discussion below provisionally establishes taxonomic relationships for correlation, although Paleogene triprojectate pollen requires more comprehensive taxonomic treatment (Parsons et al., 2001).

This discussion recommends that the *Integricorpus* species found in Mallik 2L-38, Adgo F-28 and the Caribou Hills be accepted as the same species, *Integricorpus* sp. cf. *I. reticulatus* (Mtchedlishvili) Stanley 1970, as named in Parsons (2000). This species is distinguished from: *Integricorpus* sp. A of Norris (1986), and from *Parviprojectus* sp. PJ-1 of Staplin (1976), *Parviprojectus* A of Rouse (1977) and Rouse and Mathews (1979), and *Parviprojectus* sp. A of Marincovich and Wiggins (1990) and Ridgway et al. (1995). These several *Parviprojectus* specimens are either the same species or a closely related lineage, for which the name *Parviprojectus* A of Rouse 1977 is used herein. *Parviprojectus* A also occurs once in the Mallik 2L-38 well, in the same sample (936.21 m) as *Integricorpus* sp. cf. *I. reticulatus*, indicating some overlap in their stratigraphic range.

Integricorpus sp. cf. *I. reticulatus* (Mtchedlishvili) Stanley 1970 in Parsons (2000, Chapter 4, p. 508, Pl. 7, fig. 4,5,7,12,14) looks like *Integricorpus* sp. A of Norris 1986 as shown in Norris (1997, Plate 5, figs 19-21). Parsons (2000) noted that similarity, but separated them because cf. *I. reticulatus* specimens are wider, have colps extending onto the body of the grain, have more pronounced equatorial protrusions and a coarser, stronger reticulum. However, Parsons now considers the Caribou Hills and the Adgo F-28 specimens to be the same species (pers. comm., 2001 May 3).

Adgo F-28 specimens of *Integricorpus* sp. A of Norris 1997 (Norris, 1997, Plate 5, fig 19-21) exhibit a large size range (polar/equatorial size, 28-36/10-18 μm) with equatorial projection 4-13 μm long. The exine has a very notable angular reticulum over the grain, coarser at the equator than at the poles, with a mesh diameter up to 1 μm at the equator. The reticulum also extends onto the projections, although finer than on the body of the grain.

Mallik 2L-38 specimens were referred by White (1999) to *Integricorpus* sp. A of Norris 1986. Mallik 2L-38 yielded three specimens occurring between 936.32 and 950.11 m, the lowest poorly preserved. They are triprojectate grains with a subangular microreticulum (see **0145a.tif** ([Plate 8](#), fig. 2a), **0145b.tif** ([Plate 8](#), fig. 2b); **0161a.tif** ([Plate 8](#), fig. 1a), **0161b.tif** ([Plate 8](#), fig. 1b)). On the projections the ornament becomes finely stria-reticulate to very faintly reticulate to scabrate distally. The Mallik 2L-38 specimens are similar to those illustrated by Norris (1997, plate 5, fig. 19-21) and Parsons (2000, Chapter 4, Plate 7, figs 7, 14). The Mallik specimens' polar axes are within 30-33 μm , similar to the 28-36 μm range of specimens shown by Norris (1997) and the 24-34 μm range of Parsons (2000, p. 508). The width of the Mallik specimens is 12-14 μm , within the 10-18 μm range of Norris' (1997) illustrations, and Parsons' (2000) 12-26 μm range. The equatorial projections in Mallik 2L-38 specimens are obliquely presented, but are measured at 8 μm , within the range of 7-14 μm described by Parsons' (2000).

Thus the *Integricorpus* specimens in the Caribou Hills, Adgo F-28 and Mallik 2L-38 are the same species, recognizable primarily by the coarse, subangular reticulum. Parsons' (2000)

name, *Integricorpus* sp. cf. *I. reticulatus* is accepted here because the name *Integricorpus* sp. A, used by Norris (1986, 1997) is considered to encompass two related species, as discussed below.

In his Adgo F-28 report, Norris (1997) does not separately discuss his specimen of *Integricorpus* sp. A, but uses the name from the Nuktak C-22 well (Norris, 1986). It is argued here that his Nuktak C-22 and his Adgo F-28 specimens are different, distinguishable by striate ornament versus a reticulum. This taxonomic consideration may release the Nuktak C-22 and Adgo F-28 wells from the constraint of the correlation based on *Integricorpus* sp. A.

Norris (1986, Pl. 9, fig. 12-14) synonymized *Integricorpus* sp. A found in the Nuktak C-22 well with *Parviprojectus* sp. PJ-1 of Staplin (1976, Plate 1, fig. 9,10) and with *Parviprojectus* A of Rouse 1977 (Plate 2, fig. 31). By the evidence available, this synonymy is correct, although the Nuktak C-22 specimens are poorly preserved and the specimens illustrated by Staplin (1976) and by Rouse (1977) are not available for examination. It is clear that they are, at least, closely related taxa.

The term *Parviprojectus* sp. PJ-1 was assigned to a triprojectate pollen used as a Paleogene biostratigraphic marker by Staplin (1976, Plate 1, figs. 9,10). The illustrated specimens are about 27/12 μm with equatorial projections about 5 μm long. The ornament can not be distinguished in the illustration. Rouse (1977, Plate 2, fig. 31) uses the name *Parviprojectus* A, and notes that it was reported by Staplin (1976) as a zone marker, indicating that he considered these to be the same species. From the illustration, Rouse's (1977) specimen is 28/15 μm with short lanceolate equatorial projections, and an ornament of a fine infrareticulum and an apparent polar oriented striate surface ornament.

Norris' specimens of *Integricorpus* sp. A (1986, Plate 9, figs. 12-14) are stored at GSC-Calgary; their poor preservation is evident in the figures. In size, they are 29-32/11-13 μm . The arms are too eroded for measurement or good observation of any detail, but one projection is about 3 μm long. The specimens have an infrareticulum which is so fine it is just barely visible, and at a higher focus there is a faint, polar-oriented striation, which is visible from pole to pole on the specimen illustrated in Norris' fig. 13, excepting the equatorial areas which are too eroded to determine the orientation of the striae. This is apparently the same species as *Parviprojectus* A, and not the same as *Integricorpus* sp. cf. *I. reticulatus* of the Adgo F-28 well (Norris, 1997).

In Nuktak C-22 (Norris, 1986), *Parviprojectus* A (*Integricorpus* sp. A) has a LAD of 8800 ft., well below the LAD of *Haplophragmoides richardsensis* McNeil 1997 (= *Haplophragmoides* sp. 2000) at 6920 ft. (McNeil and Birchard, 1989) so that it occurs in the lower half of the Richards and in the upper Reindeer Sequences. McNeil and Birchard (1989) give a minimum 36.6 Ma age for *Haplophragmoides richardsensis*, which is terminal Eocene or older using the Berggren et al. (1985) timescale (the Berggren et al. (1995) time scale places the Eocene - Oligocene boundary at 33.7 Ma). Although this is also an estimate of the minimum age of *Parviprojectus* A, other data suggest that its ranges higher in the stratigraphic column.

Ridgway et al. (1995, Fig. 13G) illustrate a specimen of *Parviprojectus* sp. A , which is

large (36/24 μm) with 4 μm projections, probably eroded some at the tip. The ornament is strongly striate, and there is a faint microreticulum beneath the striations. The striations are longitudinally - oriented from pole to pole, but some merge together at the equator and deflect in a direction parallel to the equator. At the equator there is a zone around the base of each projection in which the striae are approximately parallel to the equator and faint striations radiate out onto the projections. This is the best illustration of the specimens discussed here which are subsumed under *Parviprojectus* A. *Parviprojectus* occurs in Ridgway et al.'s (1995) Biozone 2, of Oligocene age (Ridgway et al., 1995).

Ridgway et al. (1995) note that their *Parviprojectus* sp. A is the same as that cited by Marincovitch and Wiggins (1990) from lower Oligocene of Unga Island. An unpublished photograph of Marincovich and Wiggins' specimen (photographs sent to A.R. Sweet by V.D. Wiggins) shows it to be similar in shape, with striate ornament and a zone of equatorially oriented striate around each projection, from which striae radiate out onto the projection. At Unga Island, *Parviprojectus* sp. A occurs in rocks that are younger than 31.3 ± 0.3 Ma, by radiometric estimate.

Other related species exist in this *Parviprojectus* group. Ridgway et al.'s specimen *Parviprojectus* sp. B (1995, fig. 13h) is dumbbell-shaped (38/18 μm). The specimen is eroded, but it has striate ornament with a faint microreticulum beneath, but no evidence of equatorial deflection of the striae, although they are very poorly preserved at the equator. The projections are small and droop, and are not usefully measurable. This variability emphasizes the need for a comprehensive study of the Cenozoic triprojectates.

As a provisional measure, it is proposed here to use the name *Parviprojectus* A of Rouse 1977, similar to *Parviprojectus* sp. A as used in several other publications. "*Parviprojectus* sp. PJ-1" has prior usage, but these names are not formal. "*Parviprojectus* A of Rouse 1977" reasonably conforms to standard binomial nomenclature and to historical usage in northern Canadian palynostratigraphy.

One specimen of cf. *Parviprojectus* A occurs in Mallik 2L-38. It is 27/14 μm , infrareticulate and faintly striate. It occurs at 936.21 m (0146a,b.tif (Plate 8, figs. 3a,b)), in the sample with the LAD of *Integricorpus* sp. cf. *I. reticulatus*, showing that the stratigraphic ranges of *Integricorpus* sp. cf. *I. reticulatus* and *Parviprojectus* A overlap, at least in part. Although the correlation between the *Integricorpus* zones of Nuktak C-22 and Adgo F-28 are is uncertain because they may be based on different species, the co-occurrence of these two taxa in core in Mallik 2L-38 indicated that the *Integricorpus* zones of Nuktak C-22 and Adgo F-28 are penecontemporaneous.

In summary, *Parviprojectus* A includes triprojectate specimens that have a very fine infrareticulum and longitudinally oriented striae. The details of surface ornament can not be compared for all specimens, but if not the same species, it is likely part of a closely related lineage. Considering the ages in Nuktak C-22 and Unga Islands, one must accept a stratigraphic range from the Eocene to the Early Oligocene. This range does not constrain the age of the distinctly reticulate species *Integricorpus* sp. cf. *I. reticulatus* but the co-occurrence of both taxa

in Mallik 2L-38 at 936.32 m, indicates that their ranges overlap. *Parviprojectus* A probably has the younger range extension of the two taxa.

Correlation of Mallik 2L-38 to the Caribou Hills Section

The Caribou Hills, on the eastern margin of the Mackenzie Delta ([Figure 1](#)), exposes a long series of outcrop sections of Paleogene age. It was described palynologically by Ioannides and McIntyre (1980), and recently in consummate detail by Parsons and Norris (1999) and Parsons (2000). Between the Late Paleocene and the ?Late Eocene/Oligocene, Parsons and Norris (1999) and Parsons (2000) identified seven fungal zones (CHF1-7), 5 alga zones (CHA1-5) and 4 embryophyte zones (CHE1-4), the uppermost being divided onto three subzones (CHE4a-c). Her data indicates the presence of the Taglu Sequence in the Caribou Hills, a southward revision of the limits of the Taglu Sequence as depicted in Dixon (1996).

No options for the correlation between Mallik 2L-38 to the Caribou Hills are entirely satisfactory. Many taxa do not occur with sufficient consistency to allow a solid definition of their local stratigraphic ranges. Arguments based on single occurrences are tenuous, because individual occurrences yield too little information about a taxon's distribution for useful conclusions to be drawn. This may be the prime reason that different taxa support different correlations.

The basal samples of the Mallik 2L-38 well are not older than Parsons' (2000) CHE4 zone because *Quercoidites*, *Ilexpollenites* and *Juglanspollenites*, which appear in succession in lower CHE4 in the Caribou Hills (Parsons, 2000), appear in Mallik 2L-38 as *Quercus*, at 1150 m, *Ilex*-type, at 1140 m, and *Juglans* at 1110 m. Moreover, older, CHE3 taxa such as *Aquilapollenites tumanganicus* and *Platycaryapollenites swasticoides* (Parsons, 2000) were not found in Mallik 2L-38 strata.

No basis was found in the Mallik 2L-38 well for identifying the lower or middle part of Parsons' (2000) zone CHE4b; *Accuratipollis bitriangularis* was not found, nor was *Ilex iliacus* separated from *Ilex*-type. The fungal spores *Ctenosporites eskerensis*, *Pesavis tagluensis*, and *Striadiporites sanctabarbarae* occur in and below sample CH-90-6-11 in the Caribou Hills, but do not occur in uppermost CHE4b or in CHE4c, above the unconformity (Parsons, 2000). They have not been observed in the Mallik 2L-38 well, arguing that the Mallik strata fit within, or above, uppermost CHE4b.

The most obvious correlation is suggested by the characteristic species *Integricorpus* sp. cf. *I. reticulatus* (see taxonomic discussion above). In Mallik 2L-38 it is found in the 936.32 - 950.11 m interval, and in the Caribou Hills as high as sample CH-90-6-12 in upper zone CHE4b. In both cases, the LAD of *Integricorpus* is below a sedimentary hiatus, which in Mallik 2L-38 occurs at 926.5 m and in the Caribou Hills occurs between zones CHE4b and 4c (Parsons, 2000). This proposed correlation is supported by sedimentological interpretation of the change of depositional environment across the unconformity/disconformity, i.e., interpreted to be from a marsh - shallow marine lower delta plain environment to a fluvial environment in Mallik 2L-38 (Jenner et al., 1999), and from delta plain and occasional marine sedimentation to fluvial-

lacustrine in the Caribou Hills (Price et al., 1980). However, the implication of a correlation based on *Integricorpus*, using Parsons' (2000) age determinations from Caribou Hills, would be that the strata below 926.5 m in Mallik 2L-38 are of Middle Eocene age.

Moreover, testing the correlation based on *Integricorpus* by patterns in other taxa leads to more questions about the validity this correlation. Chiefly, *Juglanspollenites* spp. and *Quercoidites* spp. are relatively abundant and occur consistently, yielding a better sense of their local biostratigraphic range, and they do not support the *Integricorpus* correlation. They occur in both CHE4b and 4c, both below and above *Integricorpus*. In Mallik 2L-38 they occur only below the *Integricorpus* LAD, *Juglans* below 990 and *Quercoidites* below 1000 m (although the latter has single counts at 928.01 and 905.74 m). *Accuratipollis? bitriangularis* which occurs commonly in the CHE4b (although possibly in a slump block in samples CH-90-6-46 to 49, G. Parsons, pers. comm., 29 Jan 2004), and rarely in upper CHE4c assemblage is lacking in Mallik 2L-38. *Striatocorpus sweetii* occurs 4 times below 990 m in Mallik 2L-38, but no similar grain is recorded in CHE4b, or 4c. *Pistillipollenites macgregorii* occurs commonly in CHE4b and above the unconformity in CHE4c, but only once below the disconformity in Mallik 2L-38. Relatively rare taxa, *Aceripollenites tener* and *Boisduvalia clavatites* occur rarely above and below the unconformity in the Caribou Hills (the latter possibly in a slump block in sample CH-90-6-46, G. Parsons, pers. comm., 29 Jan 2004) but occur only below the disconformity in Mallik 2L-38, but their occurrences are insufficiently consistent in one or the other sections for secure comparisons. *Magnolia magnolioides* appears once at the top of CHE4c well, but appears below the disconformity in Mallik 2L-38 (as *Magnolia* sp.). Thus, the most straightforward correlation based on *Integricorpus* appears to be seriously flawed.

Alternatively, the *Integricorpus*-bearing Mallik 2L-38 strata (936.3-950.1 m) and the some 200 m of strata below it could possibly correlate to uppermost CHE4b (above CH-90-6-11) and to the CHE4b-c unconformity. This would also imply an age of between Middle Eocene and ?Late Eocene/Oligocene for Mallik 2L-38 strata below 926.5 m, by Parsons' age interpretation. However, this correlation would not fit well with the ranges of *Quercoidites* spp. and *Juglanspollenites* spp., which occur above *Integricorpus* in CHE4c, but not in Mallik 2L-38. Also, it would also not fit well with the range of *Magnolia*, which has a FAD at 950.11 m below *Integricorpus* in Mallik 2L-38 but which in the Caribou Hills (as *Magnolia magnolioides*) has a FAD well above *Integricorpus*, in CHE4c.

Either correlation, aligning *Integricorpus*, or Mallik 2L-38 strata below 926.5 m to uppermost CHE4b and the 4b-c unconformity, implies a Middle Eocene age for Mallik 2L-38 strata, contrary to McNeil's lower limit of late Middle to Late Eocene for Mallik 2L-38 strata, based on foraminifera. This could only be resolved if the uppermost part of CHE4b were of late Eocene or younger age. This is contradicted by the occurrence of *Wetzeliella articulata* and *Charlesdowniea tenuivirgula* in sample CH-90-6-15, at the top of CHE4b, unless these taxa are responding not just to time but to environmental factors such as hyposalinity (e.g., Downie et al., 1971).

The correlation to the Caribou Hills is fraught with problems; the simplest and most

obvious correlation, based on *Integricorpus*, may be wrong. What seems clear is that the Mallik 2L-38 strata correlate to uppermost CHE4b or above; and this requires some extension of the range of *Integricorpus* sp. cf. *I. reticulatus* above its limits recorded in CHE4b. How Mallik 2L-38 and CHE4c strata interfinger is a conundrum. Of the Late Eocene/ Oligocene age proposed by Parsons (2000) for CHE4c, the Late Eocene is preferred here, inasmuch as it retains the range of *Pistillipollenites macgregorii* within the Eocene. There is clearly much more to be discovered about palynostratigraphic ranges in northern Canada. The likely synonymy of *Acuratipollis?* *bitriangularis*, and *Pseudolaesopollis* spp. (of Ridgway et al., 1995, and Long and Sweet, 1994) (G. Parsons and A. Sweet, pers. comm., 30 Jan 2004) and their relationship with *Striatocorpus sweetii* are problems that need consideration. The outcome may shed light on this correlation problem.

Correlation of Mallik 2L-38 to Adgo F-28

A critical aspect of age determination for the Mallik 2L-38 well is comparison of the palynostratigraphic patterns with the Adgo F-28 well (Norris, 1997). Interpretation is complicated by the usage for stratigraphy of both sequence and formation names, but one must fall back on an approximate shorthand which equates a formation with a sequence of the same name. Dixon et al. (1992) note that the practice in the Beaufort-Mackenzie Basin has been to use the lithostratigraphic unit that most closely corresponds to the depositional sequence to name the sequence.

Since the publication of the palynology of the Adgo F-28 well by Norris (1997), McNeil ([Appendix 1](#)) has revised the formational (sequence) stratigraphy of the Adgo F-28 well ([Figure 8](#)), based on re-examination of the foraminifera. The new stratigraphic determinations differ from McNeil and Birchard (1989) and Norris (1997) in that there is now definite recognition of a thin Kugmallit Formation, in an interval that was formerly questionably identified with the Mackenzie Bay Sequence. McNeil notes that the top and base of the Kugmallit Formation are poorly defined on logs, but estimates them at 2800 (853.4 m) and 3000 ft (914.4 m), respectively, with a well-defined base of the Richards Formation at 3360 ft (1024.1 m). McNeil's new determination confirms Dixon's and Norris' identification of Richards Formation (in Norris, 1997), which underlies the Kugmallit. However, for correlation and age determination, a significant feature of this revision is that Norris' (1997) and McNeil's ([Appendix 1](#)) interpretations of the top of the Richards Sequence differ; Norris (1997) places a Richards/Mackenzie Bay contact at 2805 ft (855 m) so the top of his *Integricorpus* Zone (2800 ft, 853.4 m), falls within in the Richards Sequence (ignoring the 5 ft (1.5 m) difference). In contrast, McNeil's recognition of the Kugmallit Formation places the top of Norris' *Integricorpus* zone in the Kugmallit Formation.

A cautious approach to the comparison of Adgo F-28 and Mallik 2L-38 stratigraphic sequences requires comparison by Last Appearance Datums (LADs). Mallik 2L-38 is a scientific borehole, drilled with chilled mud to minimize caving (Ohara et al., 1999), and this study assumes that the palynomorphs found in cuttings are generally in place, and not recycled or caved (although caving is possible and some recycling of Cretaceous palynomorphs can be demonstrated). On the other hand, the Adgo F-28 well is an industrial borehole in which caving is more likely to extend the range of taxa downhole, although Norris (1997) indicates that in some

intervals the palynostratigraphic data seem to be well constrained. This study has generally followed the taxonomy of Norris (1986, 1997), so comparison between the Mallik 2L-38 and the Adgo F-28 wells is facilitated.

A perfect alignment of LADs is unlikely because of probabilistic considerations and environmental constraints on taxa. Moreover, stratigraphic resolution between the two studies differs. In Adgo F-28 cuttings average 100 ft (30.5 m) of strata, whereas in Mallik 2L-38 resolution is at 10 m intervals in the cuttings, and at meter to centimeter scale in cored intervals. Thus, LADS which differ in Mallik 2L-38 may be lumped into one interval in Adgo F-28.

[Figure 8](#) shows the palynostratigraphy of selected taxa from Mallik 2L-38 and Adgo F-28 (Norris, 1997) in the style of a graphic correlation diagram. Both wells have been drawn to the same depth scale. Selected taxa are arranged by LADs and the projection and intersection of those lines allows estimation of a line of correlation (LOC) between the two wells. Plotted in Mallik 2L-38 are biostratigraphic indicators which occur in Adgo F-28. Thermophilous hardwood taxa, which are likely to have responded strongly to climatic cycles have not been used for correlation.

The following taxa constrain an estimated LOC between Mallik 2L-38 and Adgo F-28 (Norris 1977), considered from highest to lowest ([Figure 8](#)).

- The LAD of cf. *Lonicerapollis gallwitzii* Krutzsch 1962 occurs at 897.36 m in the Mallik 2L-38, and at 2300 ft (701 m) in the Adgo F-28 well.
- The distinctive but morphologically simple fungal spore *Hypoxylonites* has been given a generic identification in the Mallik 2L-38 well, where the LAD is at 897.36 m, just above the *Integricarpus* LAD. In Adgo F-28, the LAD of *Hypoxylonites pirozynskioides* is at 2700 ft (823 m), just above *Integricarpus* sp A.
- The LAD of the distinctive *Integricarpus* sp. cf. *I. reticulatus* occurs in Mallik 2L-38 at 936.32 m, just below the disconformity at 926.5 m. In Adgo F-28, the LAD is at 2800 ft (853.4 m).
- The LAD of *Aceripollenites tener* (Samoilovitch) Norris 1986 in Mallik 2L-38 is 944.32 m, while in Adgo F-28, at lower stratigraphic resolution, it is contemporaneous with the LAD of *Integricarpus* at 2800 ft (853.4 m).
- The LAD of *Retitriteles* sp. cf. *R. novomexicanus* (Anderson) Norris 1986 occurs in Mallik 2L-38 at 960 m and Adgo F-28 at 2800 ft (853.4 m).
- Two specimens of *Pistillipollenites macgregorii* Rouse 1962, generally considered an Early to Middle Eocene indicator (Rouse, 1977), were found in Mallik 2L-38 at 1000 m, but no specimens were found below this level. Its LAD in Adgo F-28 is 3500 ft (1067 m) (Norris 1997), in the uppermost Taglu/basal Richards sequence. In Adgo F-28, *P. macgregorii* occurs in the *Pesavis tagluensis* zone, but *P. tagluensis* was not observed in Mallik 2L-38.
- The LAD of *Psilastephanocolpites* cf. *marginatus* of Norris in Mallik 2L-38 is at 1060 m and in Adgo F-28 at 3600 ft (1097.3 m).
- The LAD of the probable fungal spore *Inapertisporites* (*Diporisporites*) *pisciculatus* in Mallik 2L-38 is at 1070 m and in F-28 at 3900 ft (1188.7 m).

The intersections of the following taxa fall distinctly off the LOC suggested by the taxa above ([Figure 8](#)). This hints at unresolved problems in the correlation.

- The LAD of *Verrucatosporites favus* occurs in Mallik 2L-28 at 785 m, and in Adgo F-28 at 2800 ft (853.4 m).
- *Desmidiospora*, a fungal palynomorph, assigned generically, in Mallik 2L-38, occurs at 935.78 m, and in Adgo F-28 at 4400 ft (1341 m).
- The LAD of *Rhoipites* cf. *R. microreticulatus* is at 960 m in Mallik 2L-38, and at 4600 ft (1402 m) in Adgo F-28.
- The LAD of the distinctive fungal taxon *Striadiporites inflexus* is at 1050 m in Mallik 2L-38, and at Adgo F-28 at 4800 ft (1463 m) (Norris, 1997).
- *Paraalnipollentias alterniporus*, the nominate species for a palynological zone in the Taglu Sequence in Adgo F-28 has a LAD at 5000 ft (1524 m) (Norris, 1997). In Mallik 2L-38, *P. alterniporus* has one occurrence as high as 890.7 m in but its interval of most common occurrence is at and below 947.61 m. This is above the *Pistillipollenites macgregorii* LAD, whereas in Adgo F-28, *Paraalnipollentias alterniporus* has a LAD 1700 ft (518.2 m) below *Pistillipollenites macgregorii*. (Other evidence indicates that *Paraalnipollentias alterniporus* ranges upwards to the Late Eocene (Long and Sweet, 1994), rather than being restricted to the Late Paleocene (as *Paraalnipollentias confusus*), as indicated by Rouse (1977)).

Although noting the taxa above as exceptions, a LOC is suggested by the cluster of taxa between 1070 and 897.36 m in Mallik 2L-38 and between 3900 and 2300 ft (1188.7 and 701 m) in Adgo F-28. This latter interval is considered and upper Taglu/Richards/lower Mackenzie Bay Sequence by Norris (1997) and upper Taglu/Richards/Kugmallit/lower Mackenzie Bay formations by McNeil ([Appendix 1](#)).

Excluding *Inapertisporites* (*Diporisporites*) *pisciculatus* and *Lonicerapollis gallwitzii*, the end members of that LOC, a more restricted correlation between *Psilastephanocolpites marginatus* and *Hypoxylonites* spp. suggests a LOC between 1060 and 897.36 m in Mallik 2L-38 and between 3600 and 2700 ft (1097.3 m and 823 m) in Adgo F-28. In Adgo F-28, this spans the uppermost Taglu/Richards and perhaps lowermost Mackenzie Bay sequences by Norris (1997) interpretation, or similarly uppermost Taglu/Richards/Kugmallit/lowermost Mackenzie Bay formations by McNeil's interpretation ([Appendix 1](#)). If one further discounts the correlation to the Taglu Sequence because of the lack of *Pesavis tagluensis* in Mallik 2L-38, one is still left with a strong argument for correlation to the Richards/lowermost Mackenzie Bay sequences by Norris (1997) interpretation, or Richards/Kugmallit/lowermost Mackenzie Bay by McNeil's interpretation. Correlation to the Richards, or Richards and Kugmallit sequences in Adgo F-28 are strongly indicated.

Biostratigraphic indicators not occurring in the Caribou Hills or Adgo F-28

Several taxa, not recorded in Nuktak C-22 or Adgo F-28 wells, nor in the Caribou Hills section, occur in Mallik 2L-38, and range in age from Eocene to Oligocene. The occurrence of

taxa identified previously in Europe is probably due to Early Eocene land bridges connecting Europe and Fennoscandia to Baffin and Ellesmere Islands via Greenland (Tiffney, 1985). The Canadian Arctic and Greenland record of these floral elements is limited. In their study of Cenozoic sequences in the Canadian Arctic and Greenland, Harrison et al. (1999) note that, "... most of the depositional record between the mid-Eocene and the mid-Pliocene is missing....", although a good record exists for the Labrador Shelf. This interval of time is well represented in strata of the Beaufort-Mackenzie Basin (Dixon, 1996).

Striatocarpus sweetii (990-1140 m) is a new species (**0173.tif** ([Plate 8](#), fig. 4), **0197.tif** ([Plate 8](#), fig. 5), **0199.tif** ([Plate 8](#), fig. 7)) ([Appendix 2](#)). In White (1999) this species was recorded as both *Parviprojectus* sp. and as *Mancicarpus* sp. of Ridgway et al. In subsequent taxonomic review and discussion with A.R. Sweet, these specimens were combined into *Striatocarpus sweetii*, a new species named after A.R. Sweet for his career-long fascination with triprojectate pollen. A. R. Sweet (pers. comm., 1999) considers this species to be an intermediate form, based on overall shape, between the heteropolar *Mancicarpus* and isopolar *Parviprojectus*. As a new species, its age significance is uncertain, but it is closely allied to triprojectate pollen of the late Eocene and Oligocene, including the likely synonymous *Acuratipollis? bitriangularis*, and *Pseudolaesopollis* spp. (above).

Cicatricosisporites paradorogensis Krutzsch 1959b (**0174.tif** ([Plate 1](#), fig. 17)), found in Mallik 2L-38 between 1000-1110 m, occurs in the Middle Eocene at its stratotype, but also occurs in Middle Oligocene continental and brackish marine rocks in Europe (Krutzsch 1967, p. 80, Pl. 22, no. 7-12). *C. paradorogensis* has apparently not been reported previously from Canada.

Boehlensipollis hohli Krutzsch 1962 (p. 272, Pl. III, fig. 18-30) (**0195a.tif** ([Plate 7](#), fig. 17a), **0195b.tif** ([Plate 7](#), fig. 17b)) occurs in Mallik 2L-38 at 1120 m. Krutzsch (1962) indicates a middle Oligocene age. A Palynodata, ver. 6.0 search, plotted by the technique of White and Jessop (2002) shows that it has been recorded in the Paleocene and Eocene, but its citation abundance increased in the Late Eocene, and Late Eocene to Oligocene is the portion of its stratigraphic range where it is most abundantly cited.

Diervilla of McIntyre (1991) is found in Mallik 2L-38 in a supplementary coal sample at 929.23 m, 2.7 m below the 926.5 m lithological boundary, and at 945.21 and 1140 m (**0203.tif** ([Plate 3](#), fig. 4)). This is a large triporate grain with baculate ornament, illustrated by McIntyre (1991, Pl. 4, figs. 1, 2) as *Diervilla*. In ornament, it is very similar to Triporate B of Piel, 1971 (p.1914, fig 150), but the pores differ. The protruding, thickened and colpoid pore morphology of this specimen is exhibited by *Ludwigia*, of the Onagraceae (Praglowksi et al, 1963, Pl. 10, 11), and it seems that this pollen more likely belongs in the Onagraceae than the Caprifoliaceae, as indicated by the name *Diervilla*. However, the name, "*Diervilla* of McIntyre (1991)" is used to compare this specimen to his specimen. This specimen was illustrated from the Buchanan Lake Formation assemblage, northeast Axel Heiberg Island, considered to be of Middle Eocene age, although a Late Eocene age could not be discounted (McIntyre, 1991).

A specimen of *Trudopollis* (**0200.tif** ([Plate 8](#), fig. 14)), found in Mallik 2L-38 at 1140 m,

is probably *T. barentsii*, occurring in a Spitsbergen flora of Paleocene to Late Eocene age (Manum 1962, p. 9, 49-50, Pl. XII, figs 24-27; Manum and Thronsen, 1986). McIntyre (1989) has found *Trudopollis* species (*Trudopollis* sp., *T. barentsii*, *T. rotundus*) in Late Paleocene assemblages from Somerset Island, and in the Iceberg Bay Formation, Axel Heiberg Island.

A probable unconformity/disconformity at 1000 m

The 1000 m horizon has sedimentological and palynological indications of an sedimentary hiatus or some other change in the regional geology of environment. In lithostratigraphy, Collett et al. (1999b) note the occurrence of dolomite between 1004 and 1005 m, underlain by a coal between 1006 and 1008 m. From a palynological perspective, the more or less continuous occurrence of recycled palynomorphs begins at 1010 m, from about 1% of all palynomorphs (Figures 3, 6, 7) and rising gradually thorough the rest of the analyzed portion of the well. The only occurrence of *Pistillipollenites macgregorii* in the well is two specimens in the 1000 m cutting sample. The relative abundance of *Laevigatosporites* increases above 1000 m, and of Ericales declines (Figure 4). The curve of Thermophilous Angiosperms/Total Angiosperms indicates a temperature decline at about 1000 m, shown as part of a more gradual trend by the curve of T-C-T/Pinaceae (Figure 10). The palynological percentage changes are not so abrupt as to suggest a long unconformity, but some diastem is suggested by the lithological and palynological evidence. The record of recycled palynomorphs suggests that this time marks the beginning of some significant regional erosional event, redepositing Cretaceous aged palynomorphs, and possibly palynomorphs of other ages. The duration and significance of this hiatus is unknown.

Summary of correlations

The presence of pollen of some thermophilous angiosperms in the interval 670 to 860 m argues that strata may be of Oligocene or Early Miocene age, similar to the Haughton Astrobleme, but the regional palynostratigraphic patterns of this interval are poorly known. By the limits of surrounding dated sections, strata between 870 and 926.5 m would be estimated to be of Oligocene age.

The correlation to the Caribou Hills is problematic, except it is clear that the Mallik 2L-38 strata from TD to 926.5 m correlate to uppermost CHE4b or 4c or above, of Middle Eocene to Oligocene age. Figure 9 is a proposed correlation diagram Mallik 2L-38, Adgo F-28, Caribou Hills. Mallik 2L-38 strata between 926.5 and 1150 m correlate with strata identified in Adgo F-28 identified as Richards, Kugmallit and possible basal Mackenzie Bay sequences, of Eocene, Oligocene to ?lower Miocene age, depending on the old scheme, or McNeil's revised stratigraphic correlation scheme for the well (Appendix 1). Other biostratigraphic indicators argue for Eocene-Oligocene ages. *Integricorpus* sp. cf. *I. reticulatus* ranges in age from the Late Paleocene to the Oligocene (using McNeil's revised interpretation for Adgo F-28). *Parviprojectus* A (936.21 m) is known to occur in the Early Oligocene although it ranges as far back as the Middle Eocene (see below). *Cicatricosisporites paradorogensis* (1000-1110 m) and *Boehlensipollis hohli* (1120 m) have Eocene to Oligocene ranges. *Diervilla* of McIntyre (929.23 to 1140 m) has been previously identified in Middle or possibly Late Eocene strata. *Trudopollis* sp. cf. *barentsii* (1140 m) is of Paleocene to Late Eocene age. *Boisduvalia clavatites* (943.73 m) is found in the Late Eocene Australian Creek Formation of British Columbia.

A Late Eocene to Early Oligocene age range is the middle of the age ranges suggested by the correlations and indicators above, but a more precise age determination is not possible. An attempt to improve this correlation is made below by using the quantitative palynological data to construct an experimental paleoclimatic signal, and using this to correlate to the North Atlantic foraminiferal oxygen isotope record. This necessitates a preliminary discussion of the record of climatic change from the Eocene to Oligocene. The question of age determination, and the rationalization of the foraminiferal and palynological interpretations, is revisited after this paleoclimatic discussion under the title “Reconsideration of Age Determinations”.

The Climatic Change from the Eocene to the Oligocene

An experimental, supplementary approach to biostratigraphy involves the use of pollen ratios to interpret the paleoclimatic signal in the palynological count data, which can be compared to other Eocene and Oligocene paleoclimatic data series. This approach is intended to refine the biostratigraphic interpretation, and improve understanding of the stratigraphic constraints of gas hydrate host rocks.

The climatic change from the Middle Eocene to the Oligocene was one of the most significant climatic and biological events of the Cenozoic, with evidence of cooling, drying and greater seasonality (see Berggren and Prothero, 1992, and papers therein). The transition from an Eocene “greenhouse” to an Oligocene “icehouse” world between 40 and 30 Ma was punctuated by major extinctions in tropical organisms at the end of the middle Eocene with a subsequent major global cooling event, and lesser extinctions in the early Oligocene. Minor extinctions took place in the Late Eocene and mid-Oligocene. The Eocene - Oligocene climatic transitions are thought to result from tectonic events. The Norwegian - Greenland Sea opened to the North Atlantic and Australia and Antarctica separated sufficiently to allow development of circum-Antarctic circulation (Prothero, 1994), although recently it has been proposed that changes in atmospheric CO₂ concentration more effectively explains the cooling (DeConto and Pollard, 2003).

Evidence from land plants shows that the Eocene-Oligocene boundary was a time of significant climatic deterioration (Wolfe, 1992). Within the general Eocene to Oligocene cooling trend, a Late Eocene temperature rise is noted by Wolfe (1992) and Wolfe and Poore (1982) (the Eocene-Oligocene boundary in that publication is considered at 34.5 Ma). They indicate that latest Eocene - earliest Oligocene leaf assemblages consistently indicate warmer temperatures than slightly older or younger assemblages.

The magnitude of the late Eocene to Oligocene temperature change in Alaska has been estimated by Wolfe (1992) using the CLAMP technique. The latest Eocene Rex Creek flora of Alaska yielded a Mean Annual Temperature (MAT) estimate of ~15° C. The Oligocene (Angoonian) assemblages, including one at Redoubt Point, Cook Inlet, yielded estimates of ~4.5° C. Wolfe (1992) estimates that the climatic deterioration occurred at about 33 Ma, about 1 m.y. after the Eocene - Oligocene boundary. In addition to temperature decline, the deterioration was accompanied by a marked increase in the Mean Annual Range of Temperature (MART).

The Eocene - Oligocene vegetation change is recorded in the Burwash Basin, Yukon

(Ridgway et al., 1995). Biozone 1, a Late Eocene assemblage, is angiosperm dominated with conspicuous pollen of warm-temperate taxa. Biozone 2, an Oligocene assemblage, is a conifer dominated, with a percentage increase of T-C-T pollen over Biozone 1, and with a change to cool tolerant angiosperms. Ridgway et al. (1995) conclude that the Eocene - Oligocene change was associated with increased wetness in the northwestern Cordillera.

Low biomass, woody savanna vegetation (without grass) developed in the Rocky Mountain region in the Late Eocene, precipitation became more seasonal, annual temperatures lowered and seasonality increased in the Chadronian, at the end of Eocene (Leopold et al., 1992). Paleosols indicate that midcontinental North America changed from humid forest to more seasonal, semi-arid open range before the Eocene-Oligocene transition (Terry, 2001).

From the palynology of the Nuktak C-22 well in the Beaufort - Mackenzie Basin, Norris (1982) reported that the palynoflora of the Richards Formation indicates temperate or warm temperate climate in the middle and late Eocene, possibly persisting to the early Oligocene, but a decrease in the diversity of palynofloras and some extinctions occurs within prodeltaic mudstone in what was then considered to be the early Oligocene part of the Richards Formation (9600-8900 ft, 2926.1 - 2712.7 m). Norris (1982) reported that thermophilous taxa, including *Ulmus*, *Tilia*, *Quercus* and *Castanea*, common in the Eocene disappear in the lower half of the early-middle Oligocene Ivik Member, and reappear higher in the late Oligocene.

A touchstone of Cenozoic paleoclimatic studies is the record of Cenozoic temperatures derived from $\delta^{18}\text{O}$ measurements of benthic foraminifera (Miller et al., 1987). Miller et al. (1987) have smoothed the isotopic data to remove frequencies higher than 1.35 My, so it is a useful record for comparison with the broad trends in palynological ratios (see below, [Figure 10](#)). The $\delta^{18}\text{O}$ curve is set on the Berggren et al. (1985) timescale that places the Eocene-Oligocene boundary at 36.6 Ma. The isotopic ratios show that, following an Early Eocene temperature maximum, there is a long but non-monotonic decline, interrupted by minor temperature peaks, circa 46 Ma and 38 Ma, a subsequent dramatic decline across the Eocene-Oligocene boundary, ending in a low temperature in the earliest Oligocene, about 35.5 Ma. In the Oligocene, there are two distinctive temperature peaks, in the early and late Oligocene about 33 and 26 Ma, respectively.

Recent work on Mg/Ca ratios from benthic foraminiferal calcite (Lear et al., 2000), have corroborated the basic patterns determined by $\delta^{18}\text{O}$ measurements, and suggest a $\sim 12^\circ\text{C}$ deep sea temperature drop over the last 50 Ma. The Mg/Ca ratios are at a lower chronological resolution than Miller et al. (1987), and use the timescale of Berggren et al. (1995), that places the Eocene-Oligocene boundary at 33.7 Ma. Within the Eocene decline, Lear et al.'s (2000) record shows a small temperature rise at ca. 39 Ma, followed by a monotonic decline to about 30 Ma, in the early Oligocene. Comparison of the $\delta^{18}\text{O}$ and Ca/Mg ratios also suggests major ice sheet expansion in the earliest Oligocene, although this event was not associated with a decrease in deep-sea temperatures.

Foraminiferal isotope records from the Southern Hemisphere provide a high resolution

record of the interval from 31 to 34.9 Ma (Zachos et al., 1996), using the time scale of Cande and Kent (1992), which also places the Eocene-Oligocene boundary at 33.7 Ma. The cold interval of the earliest Oligocene, called Oi-1, spanned about 400 kyr between 33.5 and 33.1 Ma, and included two cold peaks, Oi-1a and Oi-1b, separated by about 150 kyr. The cold episode began slowly, but the rate of temperature decline increased during the onset. The delta ^{18}O values are interpreted to indicate the existence of a continental ice volume at least 40% of modern, and a decline in bottom water temperatures of 3–4° C (Zachos et al., 1996). Cause mechanisms are potentially several, including the tectonic opening of oceanic passages between Antarctica and South America and Australia. Milankovitch -type orbital forcing may have pushed the climate from “greenhouse” to “ice-house” mode, and paced the event, but a feedback mechanism of lowering pCO₂ is indicated by delta ^{13}C measurements. A transfer of a large amount of carbon from the atmosphere to the ocean could have happened by increased CO₂ solubility in a cooler ocean, increased oceanic circulation and productivity resulting in greater marine organic carbon burial, and by erosion of exposed continental margins (Zachos et al., 1996). Recent work emphasized the significance of the carbon cycle over tectonic factors (DeConto and Pollard, 2003). Significant glaciation was limited to a brief interval during the earliest Oligocene, the recovery was slower than the onset, but temperatures did not return to Eocene values (Zachos et al., 1996).

Pollen Ratios and Correlation to Paleoclimatic Temperature Trends

Four ratios, T-C-T/Pinaceae, Thermophilous Angiosperms/Total Angiosperms, Thermophilous Angiosperms - *Ulmus*/Total Angiosperms, and *Pinus/Picea* (Figure 10), are calculated from palynological count data from Mallik 2L-38 to provide paleoclimatic proxy data and allow comparison with marine isotopic curves. All ratios sum several taxa, thus reducing the effects of stochastic variation and environmental or successional effects on individual taxa. The sums reflect both quantities and/or diversity in the summed categories. Unlike percentages, ratios suffer from no closure effect and are fully independent of each other. The ratios are minimally smoothed by a three-point moving average to emphasize trends over short term variation.

Each independent ratio is expected to respond in a general fashion to climatic warmth. This inference is based on broad scale distributional and climatic patterns of modern plants. However, as these plants have evolved since the Paleogene, and their former edaphic, climatic and competitive relationships are poorly known, only broad interpretations are possible. Other environmental and ecological variables must affect each ratio.

Within the gymnosperms, a ratio of T-C-T/Pinaceae compares two major components of the pollen record. Of all the ratios, this is based on the most abundant pollen. The T-C-T component probably represents the pollen of the Taxodiaceae family. Deciduous *Metasequoia* and *Glyptostrobus* dominated Eocene coniferous vegetation in the North American Arctic, although *Chamaecyparis* (Cupressaceae), was present (Bassinger, 1991; McIver and Bassinger, 1999). The Taxaceae were not present or too rare to be recorded. Extant members of the Taxodiaceae now grow in warm temperate forests (Hora, 1981), and their presence in the Eocene is also likely indicative of a cold month mean temperature > 0° C (Bassinger et al., 1994). In particular, the Taxodiaceae dominated the high latitude wetlands during the Eocene. Megafloral records show that the Pinaceae were also upland elements of high latitude Eocene forests, and

their presence argues for cool winter temperatures (Basinger, 1991; Basinger et al., 1994). The decline of the Taxodiaceae and rise of the Pinaceae is a significant feature of late Neogene high latitude palynostratigraphy (White et al., 1999). Today, members of the Pinaceae (*Abies*, *Larix*, *Pinus*, *Picea*, *Pseudotsuga*, *Tsuga*) dominate northern hemisphere mid- and high latitude gymnosperm vegetation (Hora, 1981). Thus, geographic distributions of modern relatives suggest that this ratio may reflect a warm to cool climatic axis.

Within the angiosperms, the ratio Thermophilous Angiosperms/Total Angiosperms serves as a broad measure of climatic warmth. Palynomorphs included in Thermophilous Angiosperms are related to modern angiosperms with distributions in temperate to subtropical areas. Thermophilous Angiosperms include *Acer*, *Aceripollenites tener*, *Carya*, *Castanea* -type, *Fagus*, *Fraxinus*, *Ilex* -type, *Juglans*, *Jussiaeae* (*Ludwigia*), *Liquidambar*, *Magnolia*, *Nyssa*, *Ostrya/Carpinus*, cf. *Planera*, *Pterocarya*, *Quercus*, *Tilia* -type, and *Ulmus* -type. Thermophiles are a relatively low proportion of all angiosperms, which includes such other abundant non-thermophilous taxa as *Alnus*, *Betula*, other triporates, and Ericales. *Ulmus*-type comprises 203 of the sum of 471 thermophiles counted below 670 m. Thus the curve is significantly influenced by its abundance. *Ulmus*-type persisted in Yukon, adjacent Northwest Territories and Alaska during the late Neogene climatic deterioration and the range retractions of other thermophiles (White et al., 1999), indicating *Ulmus*' greater tolerance for cold conditions than such thermophiles as *Liquidambar*. Because of the abundance of *Ulmus*-type pollen, a ratio of Temperate Angiosperms minus *Ulmus*/Total Angiosperms has been inset into the Temperate Angiosperms/Total Angiosperms curve. This latter ratio includes less data but eliminates the dominance of this one taxon.

Pinus and *Picea* are the most abundant Pinaceae pollen in Mallik 2L-38. In modern Pinaceae, both *Pinus* and *Picea* genera are widely distributed in the Northern Hemisphere, and show a wide range of climatic tolerances, but as a generalization, their modern distributions suggest that *Pinus* spp. are generally more tolerant of warm climates than *Picea* spp. (Hora, 1981). Thompson et al. (1999) quantify climatic tolerances of important trees and shrubs in North America. The spruces of North America grow in climates with a January temperature between -35° and 8° C, and a July temperature between 6° and 25° C. The pines of North America grow in climates with a January temperature between -31° and 32° C, and a July temperature between 6° and 32° C. Thus, spruces have slightly greater tolerance for cold January temperatures, and the same tolerance for cold July temperatures, but much less tolerance for high January and July temperatures. This may be due in part to the greater species diversity in North America of pines (50 species) over spruces (6 species). Everett (1969, p. 48) notes "As a Group, the pines favour open, windswept, sunny locations and well-drained soils. They have no need of rich earth....". Everett (1969, p. 45) notes of Asiatic spruces that "...they are found almost everywhere in the colder, moist, northern and mountainous areas." In North America and Central America, *Picea* is restricted to northern and temperate regions (Thompson et al., 1999). *Pinus* occupies most of the geographic range occupied by *Picea*, except for the northern extensions of *Picea* in Yukon/Alaska and Quebec/Labrador. Unlike *Picea*, *Pinus* occupies the central and southern region of eastern United States, California, and extends much further south in the Cordillera to Honduras. Although the cold-tolerant pines *P. contorta* and *P. banksiana* currently grow at high latitudes in

North America, during the late Tertiary pine diversity was much greater at high latitudes (Matthews and Ovenden, 1990). In summary, the ratio of *Pinus* spp. to *Picea* spp., should at least partially reflect a warm-dry (*Pinus* spp.) to cool-moist (*Picea* spp.) climatic gradient.

Patterns of the four ratios (Figure 10) through the full depth of the well confirm the general climate-driven interpretation proposed here. As expected, the T-C-T/Pinaceae ratio shows that the T-C-T category dominates in the Paleogene, and declines through to the late Neogene. Thus, the broad scale patterns of ratios fit known biostratigraphic trends and parallel the overall climatic cooling tendencies of the late Paleogene and Neogene. The Temperate Angiosperms /Total Angiosperms ratio shows that angiosperm taxa are much rarer in the late Neogene than in the Paleogene (the ratio “minus *Ulmus*” could not be calculated in the late Neogene core increment). *Pinus/Picea* ratios are relatively low in the cool late Neogene (110-118 m core increment) as compared to the warmer Paleogene, although there are intervals in the Paleogene with ratios similar to the Neogene. This ratio often shows patterns different than the others, and appears to reflect factors not influencing other ratios. The features of the four ratios are compared in the following discussion.

Below the cored interval, the stratigraphic patterns for the ratios Thermophilous Angiosperm/Total Angiosperms, the inset “- *Ulmus*” ratio, and the T-C-T/Pinaceae are remarkably similar. The earliest peak in these ratios occurs at about 1100 m. However, this is coincident with low values of the *Pinus/Picea* ratio, which had an earlier, minor peak at 1140 m. Peaks in all four ratios occur between 1050 and 1010 m. Thermophilous Angiosperms/Total Angiosperms, the inset “minus *Ulmus*” ratio, and the *Pinus/Picea* ratio show sharp declines near 1000 m.

Within the lower part of the cored interval, between 951.29- 946.21 m, there are coincident high values in two ratios, Thermophilous Angiosperms/Total Angiosperms and *Pinus/Picea* ratios, but there is no similar response in the T-C-T/Pinaceae ratio. The Thermophilous Angiosperms minus *Ulmus* inset curve shows that the angiosperm response is driven by *Ulmus* pollen. *Pinus*, which departs from mean values more than *Picea* (Figure 4a), approximately covaries with *Ulmus*-type pollen, a pattern which appears to hold over the cored interval. This edaphic or other environmental event, to which these ratios have responded, is of relative short term compared to patterns shown by cutting samples. The fact that both ratios seem to reflect the same underlying parameter is of interest, and perhaps has some longer-term interpretative value, although the explanation is unknown at present.

Within the remaining cored interval, the Thermophilous Angiosperms/Total Angiosperms ratio is variable but values remain well below peak values. Both the main curve and the inset “minus *Ulmus*” ratio show the same high frequency patterns of variation. The T-C-T/Pinaceae ratio has the lowest values within the core, and a run of low values occur between 935.78 -928.01 m. Coincidentally, Recycled Palynomorphs have a single peak at 937.36 m (Figure 3) possibly representing a short episode of increased erosion. These low T-C-T/Pinaceae values in the cored interval are the culmination of a trend which began at 1050 m. The *Pinus/Picea* ratio has generally higher values than average in the cored interval. As noted, this appears to also have

some relationship with *Ulmus*-type pollen. Within the cored interval, all ratios independently have low values near 936 m and 900 m, reaffirming short term climatic cyclicity within broader trends.

At the top of the cored interval, from 886.38 m to 880 m there is a sharp rise in the T-C-T/Pinaceae ratio, part of a rising trend which continues to 870 m. Thermophilous Angiosperms /Total Angiosperm and the inset “minus *Ulmus*” ratio has an earlier sharp upward inflection from 896.71 to 880 m, and a subsequent decline to 870 m and a following rise. Thus, although not exactly synchronous, these three ratios have very low values with subsequent rising trends across the top of the core at 886 m. The *Pinus/Picea* ratio varies, but shows different patterns than the other ratios.

Above the cored interval, there is broad peak in Thermophilous Angiosperms/Total Angiosperms and in the “minus *Ulmus*” ratio between 840 and 785 m, a subsequent decline, with a small peak at 690 m. (At 670 m the Thermophilous Angiosperms minus *Ulmus* /Total Angiosperms exceeds the base curve, which is an artifact of smoothing). The broad peak in Thermophilous Angiosperms/Total Angiosperms is coincident with a broad decline in the T-C-T/Pinaceae ratio. The subsequent peak in T-C-T/Pinaceae, centred at 750 m, is the time of a decline in Thermophilous Angiosperms/Total Angiosperms, and the converse applies for peaks and declines centred at 690 m. The *Pinus/Picea* ratio shows broad oscillations similar to the T-C-T/Pinaceae pattern.

In contrast to the pattern below 950 m, both Thermophilous Angiosperms/Total Angiosperms and T-C-T/Pinaceae ratio show out-of-phase fluctuations between 880 and 670 m. Significant vegetation change took place across the Eocene/Oligocene boundary (above), and change in patterns between the ratios may hint at reorganization of vegetation, but the actual explanation is elusive. If this 890 - 670 m interval is of Oligocene age (below), the dramatic increase in Mean Annual Range of Temperature (above) may have changed the way in which the vegetation responded to climatic warmth.

Given the age constraints of the biostratigraphic arguments presented above, and given the broad patterns and agreement of the ratios, especially within and below the cored interval, it can be argued that the palynomorphs of Mallik 2L-38 record the events of late Eocene to Oligocene climatic cooling. The change in pollen concentration ([Figure 5](#)) may be due to a change in the pollen productivity of regional vegetation from the Eocene to the post-cold period Oligocene, although climatic change could also have caused an increase in sedimentation rate.

[Figure 10](#) proposes a correlation between pollen ratios and the North Atlantic $\delta^{18}\text{O}$ record from benthic foraminifera, modified after Miller et al. (1987). The time scale for the isotopic curves is based on Berggren et al. (1985). Biostratigraphic considerations (above) generally constrain the correlation of 1150 to 670 m interval of Mallik 2L-38 to late Eocene-Oligocene interval of the isotopic curve. Considering the major features of the ratios, the T-C-T/Pinaceae best mimics the isotopic curve. In the T-C-T/Pinaceae ratio, the long decline from the peak at 1150 m to the low values at 890 m, just below the top of the core, and the subsequent sharp rise in

values, seems to mirror the Late Eocene-Oligocene $\delta^{18}\text{O}$ curve rise to its highest value (lowest temperature) in the early Oligocene. This point appears to provide the most certain correlation between these two curves. The bimodal peaks above the cored interval compare well with the isotopic curve in the Oligocene.

The correlation with the Thermophilous Angiosperm/Total Angiosperm ratio is less distinct, and would be somewhat different from the T-C-T/Pinaceae ratio. The point of correlation between the Thermophilous Angiosperm/Total Angiosperm, including the “- *Ulmus*” inset curve, and the early Oligocene $\delta^{18}\text{O}$ peak seems most likely to be at 870 m. The correlation to the Oligocene portion of the $\delta^{18}\text{O}$ record is somewhat offset from the T-C-T/Pinaceae record.

In spite of the biostratigraphic constraints, there are important *caveats* about this proposed correlation. The degree to which variation is depicted in any curve depends on the degree of smoothing. The Miller et al. (1987) isotopic curve is smoothed to remove frequencies above 1.35 myr. The pollen ratios are smoothed both by the sampling interval of the cuttings, and by a 3 point moving average. It is not proven that the smoothing of the isotopic and palynological data is similar. That certainty may not be obtainable by further analysis, but perhaps by whether the proposed correlation proves useful for future biostratigraphy and geology in the Beaufort-Mackenzie region.

The early Oligocene temperature low, with Antarctic ice accumulation, is indicated by the isotopic curves (Miller et al., 1987; Wright and Miller, 1993; Lear et al., 2000). This point is likely the most secure point of correlation to the low pollen ratios at or near 886 m in Mallik 2L-38. How the isotopic and pollen ratio curves correlate on either side of that point is less certain.

The bimodal pollen ratio patterns from 1150 to 950 m are compared with an apparent single dominant Late Eocene peak in the isotopic curve. However, a higher resolution North Atlantic $\delta^{18}\text{O}$ curve spanning 40 Ma to 6 Ma (Wright and Miller, 1993) shows a bimodal oscillation in the latest Eocene- earliest Oligocene, a pattern also observed in paleobotanical evidence elsewhere (above). Correlation to late Middle Eocene isotopic patterns (about 42 Ma), is ruled out for the basal strata of Mallik 2L-38 due to the absence of a distinct Middle Eocene palynomorph assemblage.

The Eocene-Oligocene transition falls in an interval of rise in the isotopic curves (declining temperature). Given that isotopic pattern and the correlation proposed above, the 926.5 m disconformity in Mallik 2L-38 is a likely candidate for the Eocene-Oligocene boundary.

Reconsideration of Age Determinations

An explanation for the discrepancy in age interpretation between palynomorphs and foraminifera requires a consideration of: 1) the age constraints and chronological span of *Haplophragmoides richardsensis* foraminiferal zones; and 2) the lithology and environment of deposition of sediment in the Mallik L-38 well, which bears on the nature of the foraminiferal record, and which is critical to the interpretation of Mallik 2L-38.

Age constraints on Haplophragmoides richardsensis

Haplophragmoides richardsensis, the eponymous species of McNeil's (1989) foraminiferal interval zone, is endemic to the Arctic Ocean because of severely restricted connections to other oceans during the Paleocene and Eocene (McNeil, 1989). As an endemic, the LAD of *H. richardsensis* is not well constrained by correlation to other foraminifera. Its age is estimated by its range overlap with the *Wetziella* dinoflagellate assemblage and by the age of the sub- and superjacent foraminiferal zones.

The upper limit to the *Haplophragmoides* zone is set by *Turrilina alsatica*, a widespread and reliable index fossil. The *T. alsatica* Interval Zone and the *Valvulineria dixonii* McNeil 1997 (= *Cancris subconicus*) Interval Zone (of limited distribution) are of Late and Early Oligocene age, respectively (McNeil, 1989). The top of the *Haplophragmoides* Assemblage Zone and *Haplophragmoides richardsensis* Interval Zone are placed at the top of the Eocene estimated at 36.6 Ma using the Berggren et al. time scale (McNeil, 1989; Berggren et al., 1985).

The basal age of McNeil's (1989) *Haplophragmoides richardsensis* foraminiferal zone has been constrained by the *Wetziella* assemblage. Early work reported by Staplin (1976) identified a "middle portion of the Paleogene section", not truncated by an upper unconformity. This interval contained Early and Middle Eocene dinoflagellates, including; *Wetziella hampdenensis*, *W. articulata*, *W. homomorpha*, and *W. clathrata*. Abundant fungal spores included *Pesavis tagluensis* and *Striadiporites* cf. *reticulatus*. Amongst the pollen and spores were *Pistillipollenites macgregorii*, *Taxodiaceapollenites*, castaneoid and tilioid types, other temperate climate indicators. Young and McNeil (1984) indicate that this assemblage typifies the marine shale of the basal part of the Richards Formation. Staplin's (1976) palynological information was supplemented by the analysis of several wells by Norris (see Young and McNeil, 1984, p. 21) confirming *W. cf. W. hampdenensis* as the most consistent dinoflagellate, and showing its association with a deciduous hardwood complex. This assemblage extends from 15 to 365 m above the base of the Richards Formation and to a maximum of 120 m into the top of the Reindeer Formation. The *Haplophragmoides* Assemblage Zone and the *Haplophragmoides richardsensis* Interval Zone of the Richards Sequence overlap the *Wetziella* dinoflagellate assemblage (Dixon et al., 1992). Underlying the *Haplophragmoides richardsensis* Interval Zone is the *Portatrochamina* sp. 2850 Interval Zone, which is assigned a LAD of probably > 45 Ma, based on the associated the *Wetziella* dinoflagellate assemblage (McNeil, 1989).

Wetziella is thus a critical taxon for Paleogene age determinations. Williams et al. (1998) give *W. articulata* Eisenack 1938 as the taxonomic senior synonym for *W. hampdenensis* Wilson 1967. General reviews give relatively long stratigraphic ranges for the taxon. For *W. articulata*, Powell's (1992) review gives an age of mid Early Eocene to early Late Eocene, with a range extending to the early Early Oligocene age. Williams et al. (1993) use the term *Wetziella articulata* 'complex' and give an early Early Eocene to early Early Oligocene age. In high latitude North Atlantic sites which appear to be most relevant to the Arctic Ocean biostratigraphy, the age range is more restricted. In the Labrador Sea, Head and Norris (1989) found *W. articulata*, in Calcareous Nannofossil Zones NP12, 13, and in a calcareous nannofossil barren interval, but not

in NP 15, or above. This range corresponds to a stratigraphic range in the Early Eocene and possibly early Middle Eocene. Likewise, in the Norwegian Sea, *W. articulata* is abundant in the Early?, and is rare in the early Middle Eocene, but does not occur above (Manum et al., 1989). Thus, it appears that the Early to early Middle Eocene age for *W. articulata* is appropriate for the Arctic Ocean. (The possibility, raised by Downie et al. (1971), that the *Wetzeliella* assemblage responds to hyposalinity, is an additional consideration but does not necessarily limit its value as a regional biostratigraphic tool.).

On the basis of the above, the chronological span of the *Haplophragmoides richardsensis* interval zone, using the Berggren et al. (1985) timescale, would range from 36.6 Ma to >45 Ma. On a more recent time scale (Berggren et al., 1995), this would be equate to 33.6 to >43 Ma. Thus, the *H. richardsensis* Interval Zone spans a time of about 9 myr, or more.

***Haplophragmoides richardsensis* Zone in Mallik L-38**

In Mallik L-38, McNeil and Birchard (1989) note the Richards Sequence top at 1934.0 m (6345 ft) and indicate the presence of *Jadammina statuminis* at 2300.6 m (7548 ft), which identifies the *Haplophragmoides richardsensis* Zone. *J. statuminis* is diagnostic of inner shelf biofacies, whereas *H. richardsensis* is characteristic of an outer shelf or deeper environment (McNeil et al., 1990). Thus, the foraminifera, *J. statuminis* in the Richards Sequence indicate a shallow marine environment in the lower Mallik L-38 well. McNeil et al. (1990) show that diagnostic foraminifera may be recovered in only part, generally the central part, of the sequence for which they provide chronological constraints. No sequence was identified underlying the Richards to T.D. at 2532 m (8307 ft.).

Above *J. statuminis* and the Richards Sequence top the Mallik L-38 penetrated a largely continental, deltaic sequence with only minor marine incursions. The well history log for Mallik L-38 shows that between 902.2 m (2960 ft) and 1670.3 m (5480 ft) the well penetrated sandstone, mudstone, conglomerate and coal. No coal was found below 1670.3 m (5480 ft), and lithology to T.D. at 2533.5 m (8312 ft.), is largely sandstone and mudstone. Austin and Cumming (unpublished report, 1975) erroneously place the Cretaceous - Tertiary boundary somewhere in a long, nearly barren interval between about 1493.5 m (4900 ft) and 1920.3 m (6100 ft). However, they interpret the environment of deposition throughout the Tertiary to have been, "...in the littoral zone with few indications of brackish or marine sedimentation."

Reconciliation of the Palynomorph and Foraminiferal Age Interpretations

The information presented above allows the following rationalization of the age interpretations of McNeil (1999) and White (1999). The top of the Richards Sequence in Mallik L-38 is followed by a prograding delta. In its upper strata, this delta was lithologically similar to the Kugmallit delta, based on McNeil's (1999) lithological analyses of Mallik 2L-38. This deltaic environment was apparently not suited to foraminifera, being too shallow or otherwise unsuitable. This substantiates White's (1999) explanation for the discrepancy between McNeil's (1999) record of recycled forams and White's contemporaneous palynomorphs, i.e., pollen and spores from plants living in the ponds, bogs, interfluvies and adjacent uplands were deposited contemporaneously with the sediment in a fluvial/estuarine environment, but that environment

was unsuitable for living foraminifera. Regional erosion added sediment containing recycled foraminifera and palynomorphs to that environment. Hence, a dominantly recycled foraminiferal record occurs with a dominantly contemporaneous palynomorph record.

The long span of time encompassed by the Richards Sequence and Richards foraminiferal zones, ≥ 9 myr, could accommodate deposition of at least 1605 m of late Middle and Late Eocene sediment (from 2532 m in Mallik L-38 to 926.5 m in Mallik 2L-38) and some 1374 m of fluvial/deltaic/littoral sediment between the *J. statuminis* foraminiferal top in Mallik L-38 and *Integricorpus* sp. cf. *I. reticulatus* in Mallik 2L-38. Similar fossils were deposited in strata offshore at Nuktak C-22, 27 km north, and Adgo F-28, 47 km west of Mallik L-38, in a more compressed sequence.

Kugmallit-type sediments overlie Richards sediments distally, but by the argument presented above, they appear to be facies equivalents proximally. This is different from Dixon et al.'s (1992) interpretation, who show the Kugmallit overlying the Richards distally, but separated proximally by an unconformity. The interfingered, partial facies equivalence relationship, which they attribute to Young and McNeil (1984), and as shown by McNeil (1997), is more likely correct. Pebbly mudstones of flow origin, which may be quite abundant in the Richards Formation (Young and McNeil, 1984) may have been derived from the Kugmallit facies.

These results point out that a simple short-hand equivalence of sequence and age may be appropriate for the distal part of the Beaufort-Mackenzie Basin, but may be inappropriate for the proximal part. Given that the Mallik 2L-38 sediment is considered typical of Kugmallit deltaic sediment (McNeil, 1999), Kugmallit Sequence, by the arguments presented above, also includes sediment of Late Eocene age. It is only problematic if the Kugmallit Sequence is taken as having been deposited only in the Oligocene everywhere in the Beaufort-Mackenzie Basin.

Correlation to the Caribou Hills and Adgo F-28

The Mallik 2L-38 age interpretation may have consequences for the age interpretation of the Caribou Hills section (Parsons, 2000). No correlation to the Caribou Hills is satisfactory but the simplest palynological correlation aligns *Integricorpus* below the disconformity in Mallik 2L-38 at 926.5 m to *Integricorpus* in upper CHE4b. By Parsons (2000) interpretation, Mallik 2L-38 sediments at the *Integricorpus* zone would be Middle Eocene in age, but *Haplophragmoides richardsensis* zone in Mallik L-38, 1000 m below *Integricorpus* in Mallik 2L-38, means that the age of *Integricorpus* in Mallik 2L-38 must be Late Eocene or Oligocene. This opens the possibility that the uppermost part of CHE4b (above CH-90-6-11) is of Late Eocene age. However, it is also possible that within the stratigraphic range of *Integricorpus* its distribution is interrupted several times by unconformities or environmental/climatic events, producing apparent range tops that are not correctly correlatable from location to location. This is, of course, a consideration not restricted to *Integricorpus*.

CHE4c is of ?Late Eocene/Oligocene age (Parsons, 2000). However, this could imply several occurrences of the important indicator palynomorph, *Pistillipollenites macgregorii*, in the Oligocene. In the absence of conclusive evidence of an Oligocene age, it may be best to consider

CHE4c as of Late Eocene age. Latitude may be an important consideration in the stratigraphic range of *P. macgregorii* (see below).

A graphic correlation between Mallik 2L-38 and Adgo F-28 suggest a correlation between the Mallik 2L-38 strata between 1060 and 897.36. m to the Richards, or Richards/Kugmallit/possibly lower Mackenzie Bay sequences as represented in Adgo F-28.

Relationship to Regional Tectonics

On Richards Island, seismic interpretation by Brent et al. (2005) has delineated major structural features along a 12 km, southeast to northwest transect across the Taglu Fault Zone ([Figure 1](#)). This transect is through four Mallik wells, and the offset on a major listric fault is suggested by the depths (below K.B.) to the top of McNeil's (1997) *Haplophragmoides richardsensis* foraminiferal zone which are, from southeast to northwest:

Mallik A-06, 1454.3 m (4770 ft);
Mallik J-37, 1591.5 m (5520 ft);
Mallik L-38, 2301 m (7548 ft); and
Mallik P-59, 2360 m (7740 ft).

The major listric fault lies between the J-37 and L-38, that are separated horizontally by 3 km, but have a down-to-the-northwest difference of 710 m in the top of the *H. richardsensis* zone. The Mallik L-38 wells are on the down-thrown fault block. Brent et al. (2005) conclude that the sedimentation rate is feasible that would allow the Eocene/Oligocene boundary in Mallik 2L-38 to be at 926.5 m, 1375 m above the *H. richardsensis* zone marker. Late Eocene deformation on the Taglu Fault Zone is known, and is the beginning of major Cenozoic fill in the Beaufort Sea Basin (Lane and Dietrich, 1995).

Brent et al., (2005) report two biofacies of the *H. richardsensis* zone in these wells. The proximal marine indicator, *Jadammina statuminis*, occurs in the southeastern wells A-06, J-37 and L-38. A more distal, inner to possibly middle shelf, indicator, *Bathysiphon pseudoloculus*, occurs abundantly in the northwestern P-59 well, along with *H. richardsensis* and rare *J. statuminis*. Four kilometers separate L-38 and P-59 horizontally, but there is less than 60 m difference in the top of the *H. richardsensis* marker. It is thus conceivable that the *H. richardsensis* zone strata in L-38 were deposited shallower water, and dropped to their current position through syn-depositional movement in the fault block through Late Eocene time.

Conclusions

Recycling, Ages and Tectonics

This paper argues that the palynostratigraphy of the Mallik 2L-38 well represents a primary biostratigraphic signal. It proposes the coherence of distributions as a standard to

evaluate recycling in the biostratigraphic record. It is difficult to reconcile long-term relative abundance trends, evident in the numerically dominant taxa, and dismiss the rare indicators as recycled. Many rare taxa show statistically significant clustering. However, this standard is not a panacea, indeed, a strongly patterned, but explainable trend can be recognized in the whole curve of Total Recycled Palynomorphs. Thus, these considerations assess the “balance of evidence” regarding recycling, and do not produce a definitive answer for any particular taxon.

The argument is stronger that taxa are in place when patterned distributions of fossils can be coupled with an appropriate environment, such as matching dinoflagellates to a bioturbated mudstone, or continental taxa to a coaly lithology. Both lithologies represent environments where production and deposition of contemporaneous palynomorphs is likely to predominate over recycling. In this study, most biostratigraphic indicators are not in energetic fluvial environments, but in fine grained sediment.

If one accepts the argument that most palynomorphs are in place, the age determinations that they indicate are:

110-118 m.	Late Pliocene - Pleistocene
118 - 670	unsampled and of known age
670 - 860 m	early Miocene? to Oligocene?
860 m - 926.5 m,	Oligocene
926.5 m to 1150 m.	Late Eocene.

The disconformity at 926.5 m is of uncertain duration, but probably approximates the Eocene/Oligocene boundary.

The regional evidence of active growth faults during the Eocene and syn-depositional movement on the faults (Lane and Dietrich, 1995) , plus the local identification of a major listric fault with 710 m vertical displacement between the *H. richardsensis* tops at Mallik J-37 and L-38 (Brent et al., 2005), argues that the site of L-38 was an area of active subsidence and deposition during the Eocene. This is consistent with the evidence, presented herein, of a much greater thickness of Late Eocene deposition than previously identified.

Proposed Revisions of ranges of Palynological Indicators

Mallik 2L-38 strata contain taxa which are associated with the Eocene, as described by Piel (1971), Long and Sweet (1994), and Ridgway et al. (1995). The age interpretation of the Mallik well presented above have implications for the stratigraphic ranges of several taxa.

Pistillipollenites macgregorii has been considered to be a Late Paleocene to Early to Middle Eocene indicator since Rouse (1977). *P. macgregorii* occurs in Mallik 2L-38 at 1000 m (images **176.tif** ([Plate 5](#), fig. 9), **177.tif** ([Plate 5](#), fig. 8)), in the Late Eocene, and in the Caribou Hills in the Late Eocene, if one accepts the arguments presented above. While it is tempting to dismiss its occurrence in CHE4c as due to recycling, other distinctive taxa such as *Ctenosporites wolfei*, *Pesavis tagluensis* and *Striadiporites sanctabarbarae* are long ranging in the Caribou Hills, but do not occur above CHE4b (Parsons, 1990, p. 473). Moreover, *Pistillipollenites*

macgregorii was recorded once in early Oligocene strata by Marincovich and Wiggins (1990) at Unga Island, Alaska. Thus, a biostratigraphic range extension for *P. macgregorii* into the Late Eocene, and even into the early Oligocene at lower latitude, must be entertained. *P. macgregorii*'s Eocene range suggests that it may have had a preference for a warm climate or a climate without temperature extremes. It is thus conceivable that it survived longer at Unga Island, currently at 55° North, near the moderating influence of the Pacific Ocean, than in northern Yukon, currently at 69° North, under a stronger continental influence.

In the Arctic, *Paraalnipollenites alterniporus* was first known to range through the Paleocene (Rouse, 1977), but more recent work shows that its stratigraphic range extends upwards, although its occurrence may not be common. Long and Sweet (1994) have found it in a late Eocene assemblage in the Rock River coal basin, Yukon. In Parsons's (2000) analysis of the Caribou Hills, zone CHE4c, of probably Late Eocene age (above) has one occurrence of *P. alterniporus*, but it is much more common in Early to Middle Eocene CHE3 and CHE4a,b (Parsons 2000); by the correlation proposed above, upper CHE4b may extend to the Late Eocene. The range of *P. alterniporus* has been reported to extend into the Oligocene by Ioannides and McIntyre (1980), but the reassignment of the Chadronian to the Late Eocene (Prothero and Swisher, 1992) causes the reassignment of the Australia Creek Fm. assemblage (Rouse and Mathews, 1979; Piel 1971) to which Ioannides and McIntyre correlated, to the Late Eocene (Long and Sweet, 1994). Thus the youngest firm record to date of *P. alterniporus* is Late Eocene, fitting with its occurrence in Mallik 2L-38 up to 947.61 m (**130.tif** ([Plate 3](#), fig. 8)). However, if the ages for Mallik 2L-38 have been interpreted correctly, a single specimen of *P. alterniporus* at 890.71 m is in the earliest Oligocene.

Psilastephanocolpites cf. *marginatus* Gonzales Guzman 1967 illustrated by Norris (1997, Pl. 6, figs 2,3,5, is the same as Tetracolporate B of Piel (1971, Pl. XII, figs 93, 94). This taxon is found in Mallik 2L-38 at 1060 and 1140 m (**0187.tif** ([Plate 6](#), fig. 5), **0201.tif** ([Plate 6](#), fig. 2), **0205.tif** ([Plate 6](#), fig. 3)). Following Norris (1997), White (1999) used this specimen as evidence of a Middle Eocene age but the close comparison with Piel's (1971) Tricolporate B specimens indicates that the stratigraphic range of this taxon extends upwards to the Late Eocene (Long and Sweet, 1994).

Diervilla of McIntyre 1991 ([Plate 4](#), figs 1,2) was originally recorded in the fossil forest of the Buchanan Lake Formation, northeast Axel Heiberg Island, in strata reported to be of Middle, or possibly Late Eocene age (McIntyre, 1991). *Diervilla* of McIntyre 1991 is found in Mallik 2L-38 between 1140 and 945.21 m and in a supplementary coal sample from 929.23 m, in strata of interpreted to be of Late Eocene age (**158.tif** ([Plate 3](#), fig. 1), **203.tif** ([Plate 3](#), fig. 4)). As the upper record comes from coal sample, in which recycling is very unlikely, this implies a range extension for this taxon into the Late Eocene.

Jussiaea (see Piel, 1971, Pl. XVII, fig. 152,153) recorded in Mallik 2L-38 as *Jussiaea/Ludwigia*, between 928.01 to 785 m (**116.tif** ([Plate 4](#), fig. 9)). It was originally found in the Late Eocene Australian Creek Formation (Piel, 1971; Long and Sweet, 1994). It is not recorded in the Caribou Hills (Parsons, 2000) or the Adgo F-28 well (Norris, 1997). It occurs in

the Burwash Basin in Biozone 1 of the Late Eocene age (Ridgway et al., 1995). The range in Mallik 2L-38 suggests an range from Late Eocene into the Oligocene.

Boisduvalia clavatites Piel 1971 is very rare in zone CHE4b (possibly in a slump block, above) and zone CHE4c (Parsons, 2000) of Middle and Late Eocene age (above). *Boisduvalia clavatites* is found in the Late Eocene Australian Creek Formation of British Columbia (Piel, 1971; Long and Sweet, 1994) and in Late Eocene Biozone 1 of the Amphitheatre Formation, Yukon (Ridgway et al., 1995). *B. clavatites* does not occur in the Nuktak C-22 nor the Adgo F-28 well (Norris, 1986, 1997). In Mallik 2L-38 it is found at 943.73 m (image **151.tif** [Plate 2](#), fig. 19)), also in Late Eocene rocks. Thus, it's range is apparently Late Eocene.

In Mallik 2L-38, *Diervilla echinata* is found at 740 m in probable Oligocene rocks (**101.tif** ([Plate 4](#), fig. 8)). *Diervilla echinata* has been recorded Early to early Middle Eocene beds in the Gang Ranch Big Bar area of central B.C. (Mathews and Rouse, 1984), and in Late Eocene Australian Creek Formation (Piel, 1971; Long and Sweet, 1994). Ioannides and McIntyre (1980) recorded it in the Caribou Hills in strata which are included in Parsons' Late Eocene zone CHE4c (above). *Diervilla/Weigela* has been recorded in the Yukon - interior Alaska area in beds belonging to the Cyperaceae Subzone, estimated as young as 6.15 Ma (White et al., 1999). *Diervilla echinata* and *Diervilla/Weigela* are probably equivalent, representing a modern taxon ranging back to the Early to Middle Eocene.

Lonicerapollis gallwitzii occurs in Mallik 2L-28 sporadically from 1150 m to 897.36 m well (**0133.tif** ([Plate 4](#), fig. 10), **194a.tif** ([Plate 4](#), fig. 12)). In the Adgo F-28 well, the LAD of *L. gallwitzii* occurs at 2300-2400 ft (701.0 - 731.5 m) in the Mackenzie Bay Formation, with its base at 2800 - 2900 ft in the upper Kugmallit Formation (Norris, 1997; McNeil, in White, in press). It was not observed in the Caribou Hills sections (2000). The age range suggested by these occurrences is Late Eocene to Late Oligocene/Early Miocene.

Parviprojectus sp. A of Rouse (**0146a,b.tif** ([Plate 8](#), figs. 3a, b)) was originally defined as an Oligocene indicator by Rouse (1977; Rouse and Mathews, 1979) as a result of an Australian Creek occurrence in central B.C., a record which would now be considered to be Late Eocene (Piel, 1971; Long and Sweet, 1994). *Parviprojectus* A occurs in Early Oligocene rocks in the Amphitheatre Formation, Burwash Basin, Yukon (Ridgway et al., 1995) and at Unga Island, Alaska (Marincovitch and Wiggins, 1990). The Oligocene (now Late Eocene) age interpretation was also used by Staplin et al. (1976), where the top of *Parviprojectus* A (as PJ-1) was also considered as the Paleogene - Neogene boundary in IOE Taglu C-42 and G-33. Staplin et al. (1976) indicates that the species has been found in wells off the Grand Banks, in association with *Wetzelilla articulata* and other Early to Middle Eocene fossils, and *Parviprojectus* A (as *Integricorpus* sp. A) occurs in Nuktak C-22 in the Richards Sequence (Norris, 1986; Dixon, 1990). However, Parsons (2000) did not see *Parviprojectus* A in her extensive study of the Richards and Taglu sequences in the Caribou Hills, indicating that the species is rare, and consequently, its stratigraphic range will be difficult to precisely define. If all of these occurrences are validly dated, the range of *Parviprojectus* A would appear to be from at Middle Eocene to Early Oligocene. Its occurrence may depend on climatic or environmental tolerances,

as-yet unknown.

Integricorpus sp. cf. *I. reticulatus* (**0145a, b.tif** ([Plate 8](#), figs. 2a, b), **0161.tif** ([Plate 8](#), figs. 1a, b; 2a, b)) occurs from lower CHE3 in the Caribou Hills, of Late Paleocene or Early Eocene age, to the Kugmallit Sequence of Oligocene age in Adgo F-28 (Norris, 1997; McNeil, [Appendix 1](#)).

Striatocorpus sweetii (**0173.tif** ([Plate 8](#), fig. 4), **0197.tif** ([Plate 8](#), fig. 5), **0199.tif** ([Plate 8](#), fig. 6)) occurs in Mallik 2L-38 at 990, 1040, 1130, 1140 m, below *Integricorpus* sp., cf. *I. reticulatus*. These rocks are interpreted to be of Late Eocene age. This triprojectate species is described in [Appendix 2](#).

Implications for gas hydrate accumulation

Two independent lines of evidence from the Mallik 2L-38 palynological data suggest that the top of the main gas hydrate - hosting interval at 897.25 m (Collett et al., 1999a) is a boundary or transition determined by pre-existing geological conditions. The palynomorph concentration evidence ([Figure 5](#)) points to a change of formation, sedimentation rate or pollen production in the upper cored interval, between 912 and 880 m (the precision is limited by the need to estimate some concentration values). Two independent ratios of palynomorph groups ([Figure 10](#)) also indicate that this interval records a climatic event, interpreted to be a cool period, probably the significant climatic cool event of the earliest Oligocene. The sediment overlying the gas hydrate accumulation is interpreted to have been deposited during a subsequent Oligocene warmer period, but which did not regain the warm temperatures of the Eocene. Paleogene paleoclimate did not influence gas hydrate formation, which likely happened in the Late Neogene or Quaternary periods, except indirectly through some change in regional hydrology or lithology, affecting permeability of the sediment hosting or capping the hydrate deposits.

The boundary, indicated by palynology near the top of the main hydrate hosting interval, is not detected by other geophysical logging tools (except spectroscopic gamma ray). Geophysical logging data are apparently dominated by the presence of gas hydrates, a post-depositional event. Palynology indicates a transition scarcely detected by other techniques. Thus, the top of the hydrate zone appears to be determined by pre-existing geological conditions. This conclusion is independent of the age interpretations made in this manuscript.

Summary

The Mallik 2L-38 well provided an opportunity for palynological study of a 490 m subsurface section of core and high quality cuttings of Paleogene and Neogene sediment in the Beaufort-Mackenzie Basin, to refinement of palynostratigraphy and for comparison of the continental with the marine fossil record. The conclusions of this study are summarized below.

1. On the basis of finding coherent patterns in concentration, in relative abundance of common taxa and in clustering of rare taxa, it is argued that palynomorph distributions in Mallik 2L-38

cannot be readily explained by recycling, and that the palynological record yields a primary biostratigraphic signal. The regional environment of deposition would have supported abundant vegetation which would have contributed a prodigious amount of pollen and spores to the sedimentary record. If the numerically dominant taxa are largely in place, it seems unreasonable to dismiss the indicator taxa as being largely recycled.

2. Biostratigraphy by quantitative analysis of the Mallik 2L-28 well provide the basic data, but an attempt has been made to augment and refine the age interpretation by correlation to information outside the basin, specifically by comparing the experimental paleoclimatic signal extracted from the Mallik data to the North Atlantic $\delta^{18}\text{O}$ records. This comparison argues that the Early Oligocene temperature minimum is recorded in sediment adjacent to 897 m, that is the top of the gas hydrate-hosting interval. From this reference position, the probable position of the Eocene/Oligocene boundary is identified as the disconformity at 926.5 m in Mallik 2L-38.

The palynomorph ratios used to extract the paleoclimatic data from Mallik 2L-38 have not been used in other studies, so this represents an initial attempt to provide a tool to correlate to an independent paleoclimatic signal. Obviously, the behavior of those ratios over a much longer Cenozoic section needs to be accumulated and assessed to improve the reliability of the interpretations.

3. A discussion of the taxonomy of Paleogene triprojectate fossils relevant to age determination in Mallik 2L-38 has separated *Integricorpus* sp. cf. *I. reticulatus* from *Parviprojectus* A. *Striatocorpus sweetii*, a new Paleogene species, is named. By current interpretation, it occurs in the Late Eocene. The Paleogene triprojectate lineage requires further study.

4. The discrepancy in age determination between McNeil (1999) and White (1999) is explained as a result of the termination of the foraminiferal record in a shallow marine environment, which became a marginal marine/deltaic environment. Although the *Haplophragmoides richardsensis* zone was identified in the lower, marine interval, the chronological and environmental record is then continued by continental fossils. In the area of Mallik L-38/2L-38, about 1 km of sediment was deposited during the Late Eocene, above the apparent top of the Richards Sequence. The *Haplophragmoides richardsensis* foraminiferal zone spans ≥ 9 myr, allowing adequate time for such deposition.

5. Correlation to the Caribou Hills is problematic, although it is clear that the Lower to Middle Eocene interval, below uppermost palynological zone CHE4b, is not represented in the Mallik 2L-38 well. Correlation based on *Integricorpus* is most straightforward, but is not entirely satisfactory considering the ranges of other taxa and the age implications. However, the *Integricorpus* correlation, and the time constraints of the *H. richardsensis* zone in Mallik L-38, suggests the possibility that uppermost CHE4b is of Late Eocene age, rather than of Middle Eocene age. Of the age alternatives proposed by Parson's (2000) for zone CHE4c, the "Late Eocene" age is preferred over the "?Oligocene" age. This age does not then imply a significant Oligocene occurrence of *P. macgregorii*, and a rare occurrence of *P. alterniporus*. Nonetheless, an occurrence of *Pistillipollenites macgregorii* in Alaska in Oligocene rocks at Unga Island is to be noted, but is

likely a late range extension in a more southerly and climatically moderated environment.

6. The logic of the biostratigraphic and paleoclimatic analyses presented above suggest that the Eocene/Oligocene boundary and disconformity in Mallik 2L-38 occurs within sediment identified as typical of the Kugmallit Sequence by McNeil (1999).

7. If the sequence penetrated by Mallik 2L-38 is correctly identified as Kugmallit, then some of the Kugmallit-type deltaic sediment was deposited in Eocene time. Thus, a facies relationship exists between the Kugmallit Sequence in the Mackenzie Delta and the Richards Sequence offshore, as proposed previously by McNeil (1997), and by Dixon et al. (1992, attributed to Young and McNeil, 1994).

9. The 897 m top of the main accumulation of gas hydrates appears to nearly coincide with a geologically defined boundary, shown by independent aspect of the palynological evidence, including changes in palynomorph concentration, percentages of common taxa, and in ratios expected to track paleoclimate. Although the climatic evidence is independent of the age interpretation, this interval is interpreted to be the Early Oligocene cool event. This boundary is not detected by conventional geophysical logging tools, whose records are dominated by the post-depositional accumulation of hydrates.

10. In Mallik 2L-38 there is likely a sedimentary diastem near 1000 m, and evidence from recycled palynomorphs suggests that this time in the Late Eocene marks the beginning of some regional unroofing of Cretaceous rocks.

11. White's (1999) age determinations for Mallik 2L-38 are significantly revised here but substantial uncertainties remain, in regards to the age of the sediment from 1150 to 880 m, (see above), and particularly with regard to the age range of the sediment between 880 and 670 m. This latter problem is due to the absence of useful indicator species and because of the long interval without fossil recovery above 670 m, which deprives the interpretation of the constraints from overlying biostratigraphic events. Stratigraphic range extensions may explain the late occurrences of taxa associated with the Taglu Sequence in Adgo F-28 but recycling cannot be excluded.

The age determinations argued for herein are:

110-118 m.	Late Pliocene to Pleistocene
118 - 670	unsampled and of known age
670 - 860 m	early Miocene? to Oligocene?
860 m - 926.5 m	Oligocene
926.5 m to 1150 m	Late Eocene

The disconformity at 926.5 m is of uncertain duration, but probably approximates the Eocene/Oligocene boundary.

12. The site of Mallik L-38, outboard of a major normal fault in the Taglu Fault zone, was

probably an area of active subsidence and deposition during the Eocene. This tectonic evidence is consistent with the biostratigraphic evidence of a much greater thickness of Late Eocene deposition than previously identified.

Questions for Future Research

In the discussions and tentative conclusions presented it is clear that there are many uncertainties in Cenozoic high latitude biostratigraphy. The following research objectives are suggested to be useful to refining the biostratigraphy.

1. A formal classification of Paleogene triprojectate species and accumulation of further evidence regarding their stratigraphic ranges, including *Striatocarpus sweetii* n. sp.
2. Further accumulation and consideration of the evidence for stratigraphic ranges and the influence of environmental tolerances on the distributions of important palynomorph indicator taxa, including the *Wetzeliiella* complex, *Pistillipollenites macgregorii*, *Integricarpus* sp. cf. *I. sp. reticulatus*, *Parviprojectus* A.
3. Extension of the calculation of ratios used herein over a longer chronostratigraphic range, and possibly investigation of new ratios, in an attempt to correlate within and outside the basin with data independent of sporadic occurrences rare taxa.
4. Collection and curation of quantitative biostratigraphic data from the Beaufort-Mackenzie Basin so that hypotheses can be developed and tested using accumulated sets of data. The data should include micropaleontological as well as palynological data, so the relationships between these fossil groups can be explored. Such datasets are probably the only way of approaching the question of the environmental tolerances of various palynomorphs.
5. Re-examination of an important underpinning of Late Eocene - Oligocene palynostratigraphy by re-evaluation of Australian Creek section, from which titanothere teeth provide the correlation between the palynological assemblage and the North American land mammal chronology.

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K. Miller, J. Wright and C. Lear have assisted with the North Atlantic geochemical paleotemperature record.

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Plate 8: Contains the following tif files: **0161a, b; 0145a, b; 0146a, b; 0173; 0197; 0197unsharpened, 0199; 0191; 0198; 0093; 0156; 0137; 0138; 0200.**

Note: Palynomorph measurements are for the long/short axis, or for the single longest dimension. Some palynomorph specimens may not match the size indicated in the caption because the specimen was measured at mid-focus, and then refocused on surface ornament for the image, or because an obvious tear was discounted when the specimen was measured.

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Appendix 1. Revised foraminiferal LADS for Adgo F-28

D.H. McNeil.
(11 May 2001).

New data for Adgo F-28 following examination of microslides acquired from Esso and Amoco.

1470': *A. staeschei*, poor recovery, possibly reworked or contaminated - Amoco slides
 1680': *A. magnus* (Oligocene), good recovery from 1680 to 1860', specimens iron-stained, possibly reworked or contaminated - Amoco slides
 1710': *A. staeschei* (Middle Miocene to Oligocene), very good recovery - Esso slides
 1950': *T. alsatica* (Oligocene), very good recovery - Esso slides
 2970': *V. dixonii* (Early Oligocene, one specimen), very good Oligocene assemblage - Esso slides
 [3083': casing]
 3085': last downhole occurrence of Oligocene assemblages - Esso slide
 3270': fish fragments and algal cysts typical of Richards/Taglu transition
 3450': abundant coal

Stratigraphy

Nuktak Fm: base appears to be at 1700'. A sandy zone from ~1500 to 1700' contains Miocene and Oligocene foraminifera, but the assemblages are poorly developed and are possibly reworked in a regressive or transgressive sand unit.

Mackenzie Bay Fm: top appears to be at 1700'. Base is difficult to recognize on the logs. Tentative pick is at 2800'.

Kugmallit Fm: upper contact is difficult to recognize on the logs, but tentatively picked at 2800'. *V. dixonii* at 2970' indicates probable lower Kugmallit. The lower contact occurs at approximately 3000'.

Richards Fm: top occurs at approximately 3000'. Base well-defined at 3360'.

Taglu Fm: top well defined at 3360'.

The Richards/Taglu transition is well defined in the F-28 well, based on logs, palynology, and a few microfossils. The foraminiferal recovery for the Oligocene in the F-28 well is very good, but the formational contacts between the Kugmallit and Mackenzie Bay are only tentatively picked because the contacts are not obvious on the logs. The top of the Mackenzie Bay is picked at 1700' and this is supported by the Esso slides and the logs. The Amoco slides contain Oligocene foraminifera between 1680 and 1860', but this is not matched by Esso slides and it may represent either contamination or possibly reworking (since there is a well defined sandy unit from 1500 to 1700'). In summary, the Richards Sequence is well documented in the F-28 well. The overall succession in the neighbouring Adgo J-17 is similar to Adgo F-28.

Appendix 2 . *Striatocarpus sweetii* n. sp.

Striatocarpus (Krutzsch) Farabee, Vezey and Skarvala 1991.

Striatocarpus sweetii sp. nov.

Holotype: [Plate 8](#), fig. 5. **0197.tif**, [Plate 8](#), fig. 6, **0197unsharpened.tif**, C-400771, P4364-96a, 100.1x18.3 mm, Mallik 2L-38, Depth 1130 m.

Paratype: [Plate 8](#), fig 4. **0173.tif**, C-400755, P4364-82a, 80.1x13.1 mm, Mallik 2L-38, Depth 990 m.

Diagnosis:

Small, triprojectate angiosperm pollen; subtriangular outline in equatorial view; slightly concave sides; strongly heteropolar. Exine thin; ectexine prominent, endexine not seen; semitectate, sculpture of fine striae oriented subparallel to polar axis on central body but perpendicular to the equatorial outline on the distal equatorial projections, there forming a radiating pattern.

Description:

Shape

Specimen **0197.tif** ([Plate 8](#), fig. 5), the holotype of *Striatocarpus sweetii* n. sp., and **0173.tif** ([Plate 8](#), fig. 4), are clearly presented in equatorial view and are similar in shape. The shape of the holotype is that of an isosceles to nearly equilateral triangle, the angles being near 60°. It is strongly heteropolar, and has a very reduced minor pole; in the holotype, the outline of the third equatorial projection exaggerates the size of the minor pole. The apex is broadly rounded and the maximum equatorial breadth is about three quarters of the distance from the larger pole to the base, due to the rounding of the basal angles. Specimen **0173.tif** ([Plate 8](#), fig. 4) has a similar apical angle to the holotype and is generally similar in shape but the folding of the grain makes it impossible to discern the minor pole. Both specimens **173.tif** ([Plate 8](#), fig. 4) and **197.tif** ([Plate 8](#), fig. 5) have slightly concave sides.

Size

For three measured specimens the polar/equatorial size is 18 - 20/22 µm, for a ratio of ~0.86.

Apertures

No apertures have been observed on the projections, even though one projection on the holotype is oriented so that apertures could be observed if they were well developed. Farabee et al. (1991) note that in *Striatocarpus* the colpi are never open, except in broken specimens.

Ornament

The grains are ornamented by parallel striae. The striae in the holotype are exaggerated in [Plate 8](#), fig. 6, which is image **0197.tif**, processed with an unsharp mask filter. Striae increasingly

distant from the polar axis tilt outward from that axis so that those on the distal equatorial projections appear to radiate from a central point.

Striae are faint towards the centres of the equatorial projections becoming more distinct towards the margins. The parallel striae are most prominent on the upper half of the grain, towards the apical pole, and appear prominently if the focus is on the meridional margin.

Distribution and Age:

Striatocarpus sweetii occurs in Mallik 2L-38 at 990, 1040 and 1130, below the FAD of *Integricarpus* sp., cf. *I. reticulatus*, which is at 950.11 m. Cf. *S. sweetii* occurs at 1140 m. *A. sweetii* occurs in rocks that are argued to be of Late Eocene age.

Comparative Remarks

The specimen at 1140 m, **0199.tif** ([Plate 8](#), fig. 7)(C-400772, P4364-97a, 93.9x21.2 mm, Mallik 2L-38) is referred to *S. sweetii*, and may represent the range of variation in shape in the equatorial view. This specimen occurs 10 m below the holotype, they are both the only triprojectate grains in either sample, and are of similar size, with same striae ornament. Thus, it seems likely that they belong to the same population. Specimen **0199.tif** ([Plate 8](#), fig. 7) is more rhombic with an apical angle of about 105°. The point of maximum breadth is about mid-way between poles, and the sides are nearly straight. Compared to the major pole, specimen **0199.tif**'s ([Plate 8](#), fig. 7) minor pole is indicated more by its smaller diameter and more abrupt discontinuity from the equatorial outline of the grain. The third equatorial projection, on the plane of the viewer's eyes, is bent sideways and flattened against the other projection, so the minor pole may be somewhat exaggerated by crushing. Even if the minor pole is somewhat exaggerated, the base of the grain is more rounded than the other specimens, and the maximum equatorial diameter is about midway between the poles. In [Figure 4a](#) in this study, it is included in the stratigraphic distribution of *S. sweetii*. This specimen appears to have a faint infra-microreticulum, visible at the limits of optical resolution, whereas in the holotype this feature is not visible, but is faintly visible in the paratype specimen (**0173.tif** ([Plate 8](#), fig. 4), at 990 m) at the limits of optical resolution.

Striatocarpus sweetii fits within Farabee (1990) and Farabee et al.'s (1991) description of *Striatocarpus* as containing heteropolar triprojectate species with ornament of parallel striae. Only 4 specimens of *S. sweetii* were observed, but they are distinctive enough to name. The species is named after A.R. Sweet, who has had a career-long fascination with triprojectate pollen.

In White (1999) this species was recorded as *Parviprojectus* sp. at 1040 m, and *Mancicarpus* sp. of Ridgway et al. at 990 and 1130 and 1140m. In subsequent taxonomic review and discussion with A.R. Sweet, these taxa were combined as *Striatocarpus*.

Striatocarpus sweetii is similar in ornament to a specimen of *Mancicarpus* sp. (Ridgway et al., 1995, fig. 13, I.) from the Late Eocene, Biozone 1 in the Amphitheatre Formation, Burwash

Basin, southwest Yukon, but the projections in that specimen narrow distinctly distally, and angle towards the minor pole. Farabee et al. (1991) note that Nichols has found specimens of *Striatocarpus* in the Upper Eocene to Oligocene of Alaska, however, the basis on which the age was determined is not presented (see discussion above about the reassignment of the Australian Creek Formation to the Late Eocene). Farabee et al. (1991) indicate that most species of *Striatocarpus* are restricted to the Maastrichtian of North America.

Wiggins (unpublished data) encountered a similar specimen as *S. sweetii*, identified as *Aquilapollenites* sp., in the Unga Conglomerate Member of the Bear Lake Formation of Unga Island, Alaska. The last occurrence of this taxon is in Early Oligocene strata, above a 31.0 ± 0.3 Ma potassium-argon age on biotite from a tuff bed (Marincovich and Wiggins, 1990).

Striatocarpus pyriformis (Norton) Farabee 1990, as illustrated originally by Norton (1965, Pl. 1, fig. 1-3) is unlike Mallik specimens in being overall larger and wider relative to polar axis length. Although striate, it also has evidence of exinous reticulation. *S. pyriformis* as illustrated by Farabee et al. (1991, Pl. 1, fig. 1-7) has narrower equatorial projections which extend well below the minor “pole”, compared to Norton (1965). Compared to Mallik specimens, the Farabee et al. illustration is wider with narrower and more descending equatorial projections.

Striatocarpus striatus (Funkhouser) Farabee et al. 1991, as originally described by Funkhouser (1961) is larger than the Mallik specimens, with narrow equatorial projections and width greater than the polar axis length. *S. striatus*, as illustrated by Farabee et al. (1991, Plate 2, fig. 6-8) is more rugu-reticulate than striate. However, their *Striatocarpus cf. striatus* specimens (Plate 2, fig. 1-5) are larger than the Mallik specimens, although generally wider than long and with narrow equatorial projections (excepting Plate 2, fig. 3).

Appendix 3. Palynological analysis records for Mallik 2L-38

The following is a list of the raw results of the palynological analysis of the Mallik 2L-38 well ([mallik2L 38 loggingsheets.pdf](#)). The data are listed per sample by sample depth. The listing per sample details the taxa identified, and the count of each taxon.

The listed percentages are created by Stratbugs v. 1.7, and are based on the all of the fossils in the sample. They do not correspond with the percentages in this manuscript, which are based on various sums and subsums ([Table 1](#)).