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ABSTRACT

The Mallik 2L to 5L-38 gas hydrate research wells, drilled with chilled mud to reduce caving, provide 1150 m of core and cuttings, and comprise the best subsurface material available for palynostratigraphy in the Mackenzie Delta. Quantitative palynological analysis of the kerogen fraction extracts the maximum information from the samples. It also permits the experimental approach of constructing paleoclimatic proxies by ratios of taxa in order to refine age determinations based on indicator taxa, and to correlate outside of the basin. Palynological analysis of the Mallik 2L-38 well lacks biostratigraphic information for the interval above 670 m because of sample non-recovery during drilling (except for a core between 110 to 118 m). This study of Mallik 5L-38 from 100 to 900 m fills this biostratigraphic gap and provides 230 m of overlapping section between the 5L- and 2L-38 so that analytic results can be compared. Core samples from coal beds between 933.65 and 1081.90 m yielded records of palynomorphs which are not recycled.

The identification of the recycled palynomorphs is a challenge for this analysis. Palynomorphs are separated into those deemed to be recycled, those deemed to be contemporaneous with sediment deposition, and unknown and undeterminable taxa. Taxa of Cretaceous age are clearly recycled, but if the source of recycling is strata not much older than the contemporaneous taxa, differentiation of recycled taxa from those just deposited is problematic.

In the preparation and analysis of Mallik 5L-38 cutting samples from 450 to 900 m, two fractions are identified in the organic matter, a +180 µm fraction that contains a high portion of recycled taxa, and a kerogen fraction that contains recycled and contemporaneous taxa. These two fractions are clearly differentiated by Correspondence Analysis. The differences between the +180 µm and kerogen palynological assemblages is identified only by the analysis technique of Mallik 5L-38 and the stratigraphic extent of that differentiation, and significance for palynostratigraphy, remains undefined in the broader context of the Beaufort-Mackenzie Basin. Correlation of the results from Mallik 5L-38 with palynostratigraphy from other Beaufort-Mackenzie wells is not straightforward because in other wells the +180 µm fraction was likely oxidized and released into the sample, yielding an assemblage richer in recycled taxa than the assemblages from the Mallik 5L-38 preparations.

Regional tectonic and climatic events, and their ages, are interpreted by the changes in the palynomorph and lithostratigraphic record. Taxa known to be recycled, plus the poorly preserved unknown and undeterminable taxa in the kerogen fraction above 700 m collectively record an acceleration of regional erosion, possibly representing regional uplift in the Early Miocene. Borehole erosion measured by caliper logs above 650 m also reflects discontinuities in the percentage of recycled palynomorphs and the unknown and undeterminable palynomorphs.

The Mallik 5L-38, 0 to 270 m interval is interpreted to be of late Pliocene to Pleistocene age. The interval from 270 to 340 m is dominated by the deposition of eroded material, which may represent some late Pliocene or Pleistocene glacial event more limited than a late Wisconsinan-style continental glaciation. The sub-Iperk regional erosional unconformity is identified at 340 m, with other possible unconformities at 445 and 550 m. In the interval from 340 to 700 m there is no evidence of an assemblage representing either the Middle Miocene thermal maximum or the subsequent period of decline of thermophilous taxa; hence, this interval is thought to be of Early Miocene age. The last appearance datums of *Tsuga* spp. and *Baculatisporites* spp. in this interval argue for a minimum mid-Miocene age based on comparison with Nuktak C-22 and Adgo F-28 wells. Oligocene intervals are tentatively identified from 700 to 900 m, but palynological definition of the Oligocene is problematic regionally. Although last appearance datums occur in the upper Oligocene in other studies, there is little agreement on the assemblage that marks the Oligocene. Identification of the Oligocene seems to require the recognition of intervals of more continuous occurrence of otherwise long-ranging taxa, *Baculatisporites*, *Tsuga* and Ericales, that occur in the Arnak Member of the Kugmallit Formation. The interval from 700 to 850 m may represent the Late Oligocene Chattian Age, a warm climatic interval. The 850 to 900 m interval may represent the Early Oligocene Rupellian Age, a cool climatic interval. There are similarities between the pollen zonation and the biogenic/thermogenic gas zonation.

The climate proxy ratios in the overlapping section of the 2L- and 5L-38 wells between 670 and 900 m show few similar patterns. The difficulty of comparing ratios between wells may stem from under-saturated rarefaction curves for the assemblages and from low counts with wide confidence intervals. Higher palynomorph counts are required, but may be impractical where sample volumes of cuttings are limited. It is also possible that the change from coherent, independent ratio patterns below 886 m in 2L-38 to out-of-phase patterns in 5L-38 may indicate an important stratigraphic change. The question is raised whether, in the 2L-38 study, palynomorphs from the +180 fraction were released into the kerogen, even though by a study of processing technique, that should not have happened. The significance of laboratory processing is highlighted.

An erosional unconformity about 930 m may have resulted from sea level decline due to earliest Oligocene glaciation in Antarctica.

Analysis of core samples from coal beds in Mallik 5L-38 between 933.65 and 1081.90 m yielded records of palynomorphs which can not be reasonably attributed to recycling. They confirm that Late Eocene palynomorphs occur in this interval, and show that some palynomorphs usually attributed to older Eocene rocks range into the Late Eocene. Paleontology, sedimentology, organic carbon and geochemical analysis yield a consistent picture of an upper to lower delta plain setting with a dominance of terrestrial organic matter and a varying marine influence. Limited previous dinoflagellate and forminiferal results are compatible with a Late Eocene age. A warm paleoclimate is indicated by the modern relatives of pollen from temperate angiosperms found in the coal, a paleoclimate consistent with an Eocene age.

Dominance of wetland assemblages by Ericale or Taxodiaceae-Cupressaceae-Taxaceae pollen may reflect the ecological consequences of water flow-through and pH variation. The coal swamps seem to be an environment where relict species can persist.

INTRODUCTION

Drilling History

The Mallik 5L-38 well was drilled by Japex Canada Ltd., on behalf of the Japanese National Oil Corporation (JNOC) and the Geological Survey of Canada (GSC), as a continuation of the Mallik gas hydrate research program. Mallik 5L-38 was one of three wells drilled 40 m apart in a straight line for scientific investigation and for production testing of gas hydrate deposits (Canadian Petroleum Engineering, 2002).

Mallik 5L-38 is located on Richards Island, Northwest Territories (69° 27' 39.302" N, 134° 39' 38.898" W, Unique Well Identifier 305L386930134300, NTS 107 C, Figure 1). The well was spudded on 25 January 2002 and the rig released on 14 March 2002. The Kelly Bushing (KB) was 5 m above sea level, and the well was drilled to 1166 m below the Kelly Bushing. The base of the conductor hole was 24 m KB (Canadian Petroleum Engineering, 2002). All depth measurements are assumed to be below the KB. Gas hydrates occur between 892 and 1107 m (Dallimore and Collett, 2005).

White (1999, 2003, 2009) has reported on the palynostratigraphy of the adjacent Mallik 2L-38 well. The stratigraphy relevant to this study is discussed in White (2009). In that well, palynological samples were unavailable for the interval from 0 to 670 m, except for a short cored interval between 110 and 118 m. The analysis of the Mallik 5L-38 well is to provide biostratigraphic and paleoclimatic interpretations for the 0-670 m interval, and to support and refine the biostratigraphic interpretations made in the 2L-38 well. This 5L-38 well analysis and report is based on cutting samples analysed at 10 m intervals between 100 m and 900 m, and coal samples from 192.6 m of core between depths of 885 to 1151 m (Dallimore et al., 2005). Sedimentology of the cored interval was reported by Medioli et al. (2005), geochemistry by Chen et al. (2005) and organic matter analysis by Haberer et al. (2005).

Drilling details for 5L-38 (Table 1 and Figure 2) give information that bears on the biostratigaphic interpretations. The interpretations from 116 to 650 m are based on the Platform Express: Cement Volume log. The amount of hole erosion that took place during drilling is significant for biostratigraphy as this is a measure of the rock competence and the amount of caving likely to affect sample fossil content. Caving was extensive from the base of the permafrost casing at 116 m to about 320 m, such that the hole was both much larger than the 311 mm bit, and larger than the maximum diameter of 620 mm measured by the caliper logs. From about 320 to about 560 m the hole was sometimes greater than 620 mm and sometimes less, due to some intervals being more resistant to erosion than others. At 573 m mud tanks were cleaned and shaker screens changed. Between 560 and 650 m the hole was eroded but much less than above, and there were no major washouts. The approximate base of permafrost is at 620 m. The hole was drilled to 687 m, and then casing set to 676 m, sealing the rest of the hole from caving higher up. An erosion interval at the base of casing was probably due to the circulation during casing setting. Below 675 m, interpretation is based on the Integrated Hole/Cement Volume Summary log. Below 687 m the hole was drilled with a 222 mm bit. From 687 to 762 m there is little hole erosion, and from 762 to the top of coring at 885.6 m, there is very little erosion. The base of coring was 1151 m and TD was 1166 m.

Problems and Principles guiding this study

This study of Beaufort-Mackenzie palynostratigraphy is guided by the research context, assumptions, and questions discussed below. Given those conditions and assumptions, the following analyses were undertaken, for which the results are presented below. Following is the author's best attempt to interpret their meaning. Suggestions are made for further research.

1. A pressing problem in the Beaufort-Mackenzie Basin and northern continental palynostratigraphy is the need to improve resolution of the Late Eocene, Oligocene and Early Miocene, so that ages may be correctly assigned and environmental conditions interpreted. Important palynostratigraphic work has been done by Staplin (1976), Norris (1982, 1986, 1997), Parsons and Norris (1999) and Parsons (2000) but the palynological identification of Oligocene strata remains problematic. Resolution of this problem should assist in correlation of the largely Oligocene Kugmallit Formation/Sequence.

2. Biostratigraphy is optimally done by studying a continuous section which allows inferences based on stratigraphic superposition.

3. During the Eocene many palynomorphs took on their modern form, so biostratigraphy based on evolutionaly/morphological change is less useful in post-Eocene strata than in Late Cretaceous to Eocene strata.

4. Climate has changed dramatically in the Cenozoic - from "green-house" to "ice-house". Climate is a dominant factor in determining the distributions of plants; hence, it is a dominant forcing mechanism of Cenozoic palynostratigraphy. Paleoclimatology requires quantitative analysis of regional vegetation, as assessed by pollen counts, in addition to the use of floristic indicator taxa. The decline in the vegetation dominance of the Taxodiaceae-Cupressaceae-Taxaceae (T-C-T) families and rise of the Pinaceae family is a likely proxy measure of climate change, as is the relative abundance of thermophilous (heat-loving) angiosperms whose modern relatives now may be found in China, or in the eastern seaboard of the USA to southeastern Canada (see discussion in White, 2009).

5. Ratios of these categories are a useful way of comparing them and providing a proxy measure for the direction of paleoclimatic trends. Unlike percentage calculations, ratios provide statistically independent measures from the same matrix of count data per sample. However, use of these ratios is experimental in Beaufort-Mackenzie Basin palynostratigraphy, and the results can not be compared with previous results, except with those from Mallik 2L-38.

6. A long paleoclimatic record intrinsically allows one to correlate outside of the Beaufort-Mackenzie Basin to a global pattern. The palynological record is best compared with a continuous paleoclimatic proxy record such as produced by $\delta^{18}O$ record of benthic foraminifera (Miller et al., 1987; Zachos et al., 2001). Significant events should be marked in the palynological record. The temperature decline of the Late Eocene culminating in Early Oligocene glaciation, and resulting from tectonics and a drop in atmospheric CO_2 concentration, is one of the most prominent climatic events of the Cenozoic. It is estimated to have been reflected in a temperature drop of about 8° C over 400 kyr in mid-continental North America, and in aridification in the Tibetan plateau (Bowen, 2007; DeConto and Pollard, 2003; Pälike et al., 2006; Dupont-Nivet et al., 2007; Zanazzi et al., 2007). The Late Oligocene (Chattian Age) warm interval (De Man and Van Simaeys, 2004), and the Middle Miocene (Alaskan Seldovian stage) warm interval (Wolfe,1966, 1994; Leopold and Liu, 1994; White and Ager, 1994; White et al., 1999) are paleoclimatic events that should show prominent palynostratigraphic signatures. In the Middle Miocene Seldovian Stage, a thermophilous, rich flora with abundant T-C-T pollen occurred as far north as the Upper Ramparts Canyon (White and Ager, 1994). The palynological signature of the Chattian Age needs (Norris, 1982, 1986) further definition.

7. A climatic signal indicating direction of change can be obtained by summing climate-sensitive taxa, thereby reducing stochastic variability. Amalgamation of taxa to produce higher numbers for analysis has proven a fruitful tool in other biostratigraphic studies (e.g. White and Leckie, 1999). This complements the use of individual, rare indicators whose distributions have considerable statistical noise. The climate tolerances of the modern relatives of late Paleogene and Neogene fossil taxa are useful guides to interpretation of paleoclimates (Utescher et al., 2009).

8. The Mallik 2L-38 and 5L-38 gas hydrate research wells have yielded the best material available in the Beaufort-Mackenzie Basin for the study of the late Paleogene and Neogene because they were drilled with chilled mud to minimize caving, cuttings were sampled at 5 m intervals and core at centimetre-scale intervals, and extensive logs and other scientific analyses are available. These Mallik wells yield about 1 km of Cenozoic section, spanning the Late Eocene to the Plio-Pleistocene.

9. Palynomorph recycling is a vexing problem in Beaufort-Mackenzie palynostratigraphy in the mid- and Late Tertiary. This is due at least in part to an active tectonic regime (Lane and Dietrich, 1995). Recycling from much older rocks is relatively easily detected by taxonomy or thermal maturity differences (Stanley, 1966; Staplin, 1969), but the less time elapsed between the age of the source rocks and the subsequent redeposition, the greater the difficulty in detecting recycling (Playford and Dettmann, 1996). The quality of preservation of palynomorphs may be helpful, but is not conclusive because palynomorphs recycled in clasts can be preserved in excellent condition.

10. Palynologists may make arbitrary determinations that individual specimens are recycled, and they may be correct. However, such determinations usually do not come with convincing supporting evidence and ignore of the possibility of range extensions and floristic responses to paleoclimatic events such as warm episodes. The recycling of one specimen implies the recycling of others, compromising the assemblage. As a complement to measures of recycling based on individual specimens, it may be useful to assess the evidence regarding the whole assemblage, especially when the recycled palynomorphs may be derived from strata not much older that the sediment being deposited.

11. Throughout most of the Cenozoic in Arctic Canada, a rich vegetation of gymnosperms and angiosperms existed that should be represented by pollen and spores in sediment. Pollen production must have been substantial and contributed copious pollen to the sediment via airborne and waterborne transport. Only modern desert and tundra vegetation produce so little pollen that it scarcely contributes to the regional pollen rain, and there is no indication that such environments existed in the Canadian Subarctic and Arctic regions during most of the mid-Cenozoic. At our present state of knowledge, it is only during the late Pliocene and Pleistocene that one could imagine regional vegetation producing very little pollen. Under such conditions, sediment would receive little pollen from local or regional vegetation, so that recycled pollen could be a dominant component of organic sedimentation. Even then, it should be noted that pollen deposited in modern tundra environments has a component of pollen transported from the forests to the south, reflecting vegetation distant from the tundra, so recycled pollen would not be the only contributor to a sedimentary record. It is difficult to imagine a mid-Cenozoic environment where the dominant contributor to the sedimentary palynomorph record was recycling.

12. A taxon may exhibit a well-defined biostratigraphic range in an environment with a constant, low sedimentation rate, such as a marine environment. In a continental, alluvial environment with an episodic regime of rapid sedimentation and intervening unconformities, the

biostratigraphic record will be more irregular and the true range harder to interpret.

13. It is important to try to delineate the basic biostratigraphic/paleoclimatic signal. If one is familiar with a musical score, one will recognize it from only a few bars when played in a bandstand across a noisy street. If one does not know the music, one hears only sounds. The process of biostratigraphy is that of trying to capture the whole score by meticulously transcribing the notes as the opportunity presents, so that one may eventually recognize only a few bars.

METHOD

Recycling and Caving

Palynologists working on late Paleogene and Neogene sediments in the Beaufort-Mackenzie Basin face the problems of often sparse palynomorph recovery, and potentially extensive recycling of palynomorphs. Additionally, significant caving occurs in industrial wells, but is less of a problem in the Mallik 2L and 5L-38 wells, which were drilled with chilled mud to reduce permafrost melting, and hence caving (above).

Sample Processing

The preparation of the samples from Mallik 5L-38 was modified during palynological analysis to optimize recovery from sparse samples and to more fully analyse the palynomorph yield of the sediment samples.

Samples of washed cuttings or core were weighed and 2 tablets of acetolysed *Lycopodium* spores (Lund University, Batch 938934) were added per sample to permit measurements of pollen concentration in the preparations (Benninghoff, 1962). Samples of 13 to 20 grams weight were macerated with standard HCl and HF treatment and the residues were screened using 180 and 10 µm nominal meshes, removing the fraction ≥254 µm and ≤14 µm (Table 2) (except the interval from 270 to 345 m, where a 7 µm mesh was used for screening, but was found to make processing too difficult). The 180 µm screen removes detritus in sizes larger than all terrestrial palynomorphs, thus increasing the palynomorph concentration. Also, the removal by the 10 µm screen of the fine detritus in the preparation makes it easier to find palynomorphs. The acid- resistant organic matter has not been oxidized during this maceration, so this preparation is called “kerogen” here, although it does not meet the rigorous definition of kerogen (Batten, 1996) and is not suitable for characterization of environment of deposition.

Oxidation during processing may change palynomorph colour (Wood et al., 1996), and the intent of working with kerogen was to permit the colour of the palynomorphs to be observed. Colour provides evidence for detecting recycling, but it is not a perfect index because the thickness of the palynomorph strongly affects its apparent colour, and because recycled palynomorphs have not always had a diagenetic history that would cause colour change.

Coal samples from core below 900 m (below) were macerated by HCl, HF and 5 minutes of hot Schulze treatment and screened by hand through 180 and 10 μm meshes. Residue from the HCl and HF treatment that was not coaly was acetolyzed and mounted. These latter slides yielded some organic detritus and very sparse palynomorphs.

Laboratory sample processing for Mallik 5L-38 (Table 2) started from the top of the well, working down in 5 m intervals, although microscope analysis was reduced to 10 m intervals because, during the analysis, it was recognized that two fractions of the same sample should be analyzed. At 450 m and below, L. Dancey, the preparatory, noticed a considerable amount of organic matter on the 180 µm nominal screen whereas normally little was observed and it was routinely discarded. That fraction retained on the screen was oxidized for 5 minutes in hot Schulze solution with a base neutralization to release the palynomorphs, then screened through 180 and 10 µm screens, mounted as slide B (L. Dancey, pers. comm., 2 December 2004), and analysed separately.

In order to permit comparison of the palynological data from oxidized and kerogen fractions, the oxidized residue analyses were recorded in Stratabugs at a false depth that is 3.66 m below the true sample depth. Thus they separate in a plot. (The +180 µm data were assigned to the analyst name “FRACT” in Stratabugs so that it could be separately identified and exported for analysis. The kerogen data were retained under analyst name “JMW”.)

Kerogen preparations generally yielded low pollen concentrations, yet the kerogen preparations below 550 m gave extremely poor recovery, requiring an improvement in palynomorph concentration. Stored kerogen residue was acetolysed to remove fine organic detritus. Acetolysis has the effect of darkening palynomorphs, reducing the applicability of the palynomorphs colour analysis, although the relative scale between very dark and light palynomorphs still exists. The reduction in organic detritus adhering to the palynomorphs allowed improved identification in taxa such as the triporates and Pinaceae. A comparison of palynomorph yield from acetolysed and non-acetolysed kerogen samples for 580, 590 and 600 m is found in Table 3.

Counting and Summation Procedures

The palynomorphs in kerogen fraction slides were counted but the sums were low because of poor concentration of palynomorphs. A total of 6241 palynomorphs were tallied in the 76 countable cutting samples between 110 to 900 m, yielding 82.12 ± 36.5 palynomorphs per sample. Samples at 140, 150 and 160 m were barren. The oxidized fraction was scanned for taxa, and they were recorded as presence/absence data.

Taxa identified in the kerogen fraction of Mallik 5L-38 were allocated to various groups (Table 4). Some taxa may occur in more than one category - i.e., as both an angiosperm and an angiosperm with temperate climatic affinities. The "1" in Table 4 indicates the taxon's category, but a "?" in the Recycled column indicates the uncertainty of its status. For instance, *Cicatricosisporites* spp. and *Stereisporites* spp. are long ranging taxa, and could be recycled from the Cretaceous but many similar forms can be found in the Early and mid-Tertiary (see Krutzsch, 1963, 1967a).

The identification of a taxon as being recycled or in-place ("contemporaneous" with the sediment in which it is found) is a particularly difficult task in Beaufort-Mackenzie mid- and Late Tertiary palynology because of the modernization of the flora in the Eocene (above) and because there may be minimal thermal maturity or preservational differences between fractions. The philosophy of this work is not to categorize palynomorphs as recycled unless there is clear taxonomic, thermal maturity or preservational evidence to support that decision.

The analyses that follow endeavour to reveal patterns amongst definitely recycled, suspect recycled, and contemporaneous palynomorphs. These patterns can then be interpreted with regard to the integrity of the pollen record and correlated to regional and global events.

Calculation of Pollen Ratios

Pollen ratios of selected pollen taxa were calculated for Mallik 5L-38 pollen assemblages to serve as statistically independent, trial proxies for paleoclimates. The taxonomic groups used in these calculations follow those described by White (2009) in the analysis of Mallik 2L-38. A three-point moving average function has been applied to all curves for minimal smoothing of noise. The composition of ratios and the climatic and ecological tolerances of the taxa are discussed in White (2009), and are reviewed briefly here.

Within the gymnosperms, a ratio of Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae compares two major components of the pollen record. The geographic distributions of the modern relatives of these taxa suggests that a decrease in the T-C-T/Pinaceae ratio may reflect a warm to cool climatic trend. Of all the ratios, this is based on the most abundant pollen. The T-C-T component probably represents largely the pollen of the Taxodiaceae family (including *Sciadopitys),* abundant at high latitude through most of the Cenozoic. The name *Inaperturosporites dubius* has been used for pollen which appears to have T-C-T affinities, and it is included in the T-C-T category, but the curve of T-C-T minus *Inaperturosporites dubius*/ Pinaceae has also been calculated for comparison with the former curves [The ratios T-C-T / Pinaceae and T-C-T minus *Inaperturosporites dubius*/Pinaceae, (below) are very similar, arguing that the grains classified as *I. dubius* are indeed T-C-T pollen.] Members of the Pinaceae include *Abies, Larix, Picea, Pinus, Pseudotsuga* and *Tsuga* spp.

Within the angiosperms, the ratio Temperate Angiosperms/Total Angiosperms serves as a broad measure of climatic warmth. Palynomorphs included in Thermophilous Angiosperms are related to modern angiosperms that have distributions in temperate to subtropical areas. The list of Temperate Angiosperms is impoverished compared with the Mallik 2L-38 well, but includes *Acer*, *Carya*, *Ilex* -type, *Magnolia*, *Pterocarya*, *Tilia* -type, and *Ulmus* -type. The thermophiles are a relatively low proportion of all angiosperms, which includes other abundant, non-thermophilous taxa such as *Alnus*, *Betula*, other triporates, and Ericales. In the analysis of Mallik 2L-38, a curve of Temperate Angiosperms minus *Ulmus*-type was generated, and it is also calculated here for comparison.

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. 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.

IDENTIFICATION OF RECYCLED AND CONTEMPORANEOUS FRACTIONS IN THE MALLIK 5L-38 WELL

The following discussion considers the identification of the depositional vectors for recycled and contemporaneous (non-recycled) palynomorphs. These groups are differentially represented in the two sedimentary fractions separated during laboratory preparation. Recommendations are given for the preparation of samples. Consideration is given to the comparability of the Mallik 5L-38 results with the 2L-38 results (White, 2009). Following this discussion is an interpretation of the geological significance of the recycled fraction, and a paleoenvironmental and biostratigraphic interpretation of the kerogen fraction. Recommendations are made for future work.

Sources and Transport of Palynomorphs, Identification of the Recycled and Contemporaneous Fractions and Sample Processing Recommendations

Transport and deposition of contemporaneous pollen and spores

Most of the pollen and spores recorded in temperate and northern Cenozoic sediments are anemophilous, i.e., are carried by air currents from anthers to pistil. Some pollen and spores are entomophilous, carried by insects, and some aquatic plants release pollen directly into the water. Rivers passing through a riparian environment pick up a significant load of pollen and spores from the adjacent vegetation, mostly from the airborne pollen rain, and these palynomorphs end up as sedimentary particles in water bodies, where they are transported and deposited with the silt and clay fraction. These are called “contemporaneous” palynomorphs in the follow discussion because they reflect regional vegetation living just before and during their transport and deposition. Palynomorphs are largely transported through environments where sand and coarser fractions are deposited, and settle with fine silt and clay.

Rivers erode flood plain deposits of pollen- and spore-rich peat or mud, perhaps many thousands of years old, but on a geological time scale, these palynomorphs are indistinguishable from the contemporaneous palynomorphs. They would add to the component of the pollen in the sediment which reflects vegetation. Rivers carry enormous loads of pollen to the delta and to sea, reflecting regional and riparian vegetation (Muller, 1959; Heusser, 1978) and the abundance of contemporaneous pollen can swamp the amount of recycled pollen (Muller, 1959).

The concentration of palynomorphs in sediment depends on regional pollen productivity, the sedimentary environment (organic or clastic dominated), the rate of sedimentation (hence the dilution of the organic matter), and the ability to collect organic-rich horizons in the sediment during sampling. A few organic-rich horizons between sandstones may be individually pollen-rich, but if sampled in drill bit cuttings, may yield palynomorph-poor preparations. Poor to very poor pollen productivity is a general problem in the analysis of the Mallik wells, except for the cored intervals where organic-rich beds can be individually sampled (below; White, 2009).

Erosion, transport and deposition of recycled palynomorphs

Recycled pollen and spores enter the assemblage in two ways. Clasts of coal or peat, sufficiently competent to stay together, can be eroded in a fluvial environment and redeposited with the sediment; this is the probable source of the recycled palynomorphs found in the + 180 µm fraction and released by hot Schulze oxidation (below). An additional source of recycled palynomorphs is mudstones or shales, as old as the coal or peat, that would also be eroded, but (depending on diagenetic cement) would more likely be broken up during transport to release their palynomorphs as separate sedimentary particles. The palynomorphs from this clastic fraction would likely be more corroded than those transported in an organic clast. Therefore, they would be more likely be recorded as “Recycled”, or possibly as “Undeterminable”, depending on the state of preservation and the degree of taxonomic information present. Muller (1959) noted that reworked Tertiary pollen was easily distinguished from Recent pollen by its flattened shape and poor preservation, and it was relatively most abundant in Orinoco River levees.

If shale or mudstone clasts do not break up, their enclosed palynomorphs could be preserved in excellent condition, to be released by HF and HCl treatment of the sample. The discussion below shows that sample preparation technique influences the degree to which different components are represented in the palynological results.

Comparison of preparation techniques for cuttings in Mallik 5L-38 and 2L-38 wells

The Mallik 5L-38 analysis is a complement to the analysis of the 2L-38 well, but within the general objective of analysing kerogen in both wells, preparation techniques had to be adjusted to overcome problems of poor palynomorph productivity. As preparation techniques vary in their ability to release palynomorphs from the various organic and inorganic fractions of sediment, it is important to compare the preparation techniques for the two wells. Important questions are: 1) are the kerogen results from the 5L-38 and 2L-38 wells comparable, and; 2) do the Mallik 5L-38 kerogen and +180 fractions differ and if so, why ?

A comparison of processing techniques for the 2L-38 and 5L-38 wells is found in Table 2. Mallik 2L-38 samples, after HCl and HF digestion were given a +180 µm and an ultrasonic -7 µm mesh screening, yielding a fraction for analysis between ca. 210 and 10 µm (the diagonals of the nominal mesh sizes) (White, 2009). Any fraction retained on the +180 µm mesh was discarded without record of the amount. The -7 µm mesh fraction, too small for virtually all palynomorphs, was washed away. The kerogen fraction was then given a light oxidation with cold Javex and neutralized with ammonium hydroxide to improve concentration by removing fine detritus, and this fraction was analysed. For Mallik 5L-38 samples, the kerogen fraction was used for analysis of contemporaneous pollen, but this fraction did not receive cold Javex treatment. The chief difference between 2L-38 and 5L-38 processing was that for 5L-38, from 450 to 900 m, the +180 µm fraction was retained and its palynomorphs released by strong oxidation. This latter step yielded preparations that have a greater representation of recycled palynomorphs.

Not all organic clasts containing recycled palynomorphs would be larger than +180 µm nominal mesh, and so one assumes that some were not filtered out by this screening. Smaller clasts could have entered the kerogen residue in both 2L-and 5L-38 analyses. Hence the question – in 2L-38, could the brief treatment of cold Javex and base have released into the kerogen residue the recycled palynomorphs that would have been excluded in the 5L-38 processing?

This question was tested by a maceration experiment done at GSC-Calgary in November, 2010. A lignite sample from the Poplar River Mine, Saskatchewan (C-190091, P3672-3) was divided, and one half was treated with hot Schulze solution and the other half with hot, full-strength bleach (sodium hypochlorite, 10.5%) for about 5 minutes. Both were followed by an ammonium hydroxide neutralization. The hot Schulze solution effectively macerated the lignite and released a flood of hundreds of palynomorphs per field of view. On the other hand, the hot bleach treatment left much of the coal unmacerated and released perhaps 5 % of the palynomorphs released by the Schulze solution. Another sample of the same coal was crushed and treated with a cold, dilute bleach solution (~5%, sodium hypochlorite) for 5 minutes and then a base, which is likely a similar but a longer bleach treatment than given the original Mallik 2L-38 samples. This preparation gave a minimal yield of 2 or 3 palynomorphs per field of view, less than 1% of the yield of the hot Schulze treatment. This experiment would lead one to conclude that there was not significant contamination of the 2L-28 samples by a light Javex treatment, but one can not rule out any contamination. Therefore, it seems likely that light Javex and base treatment in 2L-38 would have a minimal effect on the comparability of analyses of the two wells.

One other technique difference must be noted. The screening to remove very fine detritus was by ultrasonic probe in 2L-38 preparations, and by hand in the 5L-38 preparations. The high energy ultrasonic probe conceivably reduced organic clasts in 2L-38 so that a light oxidation and base treatment might have released their palynomorphs, yielding a higher proportion of recycled palynomorphs. Current data do not allow this possibility to be evaluated, and it must be kept in mind for future research.

The nature of organic matter retained on the 180 µm screen in 5L-38 is uncertain. Coal typically leaves large undigested particles on the bottom of the beaker after HF digestion on the stirring table. This was not observed in Mallik 5L-38 (L. Dancey, pers. comm., 2 Dec 2004). Moreover, in the Mallik 2L-38 well, only one of the sample records had "?coal" noted. If it is coal, it is too finely divided to be identified with the naked eye. It was thus likely an indurated peat.

Comparison of species compositions of Mallik 5L-38 kerogen and +180 µm cuttings fractions using Correspondence Analysis

A key question in determining if there is a useful biostratigraphic signal in the 5L-38 data is knowing if the recycled palynomorphs are concentrated in a particular sedimentary fraction. Perusal of the +180 µm species records suggests that this fraction contains a significant portion of recycled palynomorphs, but the kerogen fraction also contains recycled palynomorphs. This would be expected considering the potential vectors for recycled palynomorphs discussed above. However, one must examine how these fractions differ and if there might have been cross-contamination between fractions during processing?

Species lists suggest that minimal cross-contamination occurred between the +180 µm fraction and the kerogen during processing. *Sciadopitys* occurs consistently in the +180 µm fraction, and is absent in the kerogen fraction. Conversely, no acetolysed *Lycopodium* spores from the exotic spike tablets were found in the +180 µm fraction, although the +180 µm organic particles sat in the same acid solution with the kerogen, and were exposed to the concentration of acetolysed *Lycopodium* spores from the exotic spike tablets. This evidence argues that the two preparation fractions represent different components of the geological record, rather than artifacts of preparation.

Determining how the two fractions differ requires more analysis. The data collected for the kerogen samples is quantitative. The data for the +180 µm fraction is presence/absence (nominal) data, collected to taxonomically characterize that fraction. Consequently, comparisons must be on the basis of presence/absence data.

Comparison of taxa can be done by inspection of the plot of Mallik 5L-38 palynomorph data (Figure 3) plotted alphabetically by group. This relative abundance plot presents the occurrences of taxa along with the qualifier, "?", to denote questioned identifications. In this plot, samples from 450 to 900 m have replicate kerogen and +180 μm records. The kerogen fraction of samples (StrataBugs analyst JMW) is plotted in blue and the +180 µm fraction (StrataBugs analyst FRACT, plotted 3.66 m below true depth) is plotted in green. Some taxa dominate in one or the other fractions. For example, *Lycopodium* spike (exclusively), *Betula* <= 20 µm, *Betula* >= 20 µm, and *Shepherdia canadensis* occur mostly in the kerogen fraction. Other taxa occur mostly in the +180 µm fraction, e.g., *Sciadopitys* sp., *Hamulatisporis* sp., *Gleicheniidites senonicus*, Polypodiaceae-Dennstaedtiaceae form 1. The pattern of occurrence of other taxa is less clear, and many taxa are long-ranging and could legitimately occur in both fractions even if the +180 µm fraction represents more recycled taxa. A more sophisticated analysis of this data matrix is required.

Correspondence Analysis (CA) is an appropriate technique for reducing the dimensionality of presence/absence data where many of the matrix values are “0", and CA ordinates for both samples and taxa (Kovach, 1989; 1995a, b; 1998). Correspondence Analysis was performed using the Multivariate Statistical Package (MVSP), Version 3.13 (Kovach Computing Services, 2004). Data from the pollen and fern spore data subset was used for the analysis, for it represents the greatest taxonomic diversity and highest certainty of identification. Samples included were from 450 m to 900 m (“903.66" m for the +180 µm sample), comprising 45 samples, each having paired analyses of kerogen and the +180 µm analyses. CA was done using a Cyclic Jacobi algorithm constrained to 10 axes.

The data are characterized by high variability and high “beta diversity”, or species changeover, typical of biostratigraphic data (Kovach, 1989**.** After preliminary analyses, it was decided to improve the consistency of occurrence of taxa by combining, where possible, species at the genus level, an approach that proved fruitful for White and Leckie (1999), e.g., all *Cicatricosisporites* species were combined to Sum *Cicatricosisporites*. After this taxonomic summation, all taxa that had only one occurrence were deleted from the analysis, in spite of potential biostratigraphic significance. A further analysis showed that samples 483.66 and 513.66 m were outliers on Axis 1, which have a disproportionate effect on Correspondence Analysis (Kovach, 1995b). On inspection, they were found to have very limited representation of taxa, so they were also deleted from the subsequent analysis to allow more spread of taxa on Axis 1 and improved visual interpretation. Sample 653.7 m is an outlier on Axis 2, but has a reasonably rich palynomorph assemblage, and was retained in the analysis.

The Correspondence Analysis eigenvalues show that this is a “noisy” data set with many sources of variability. The eigenvalue for the first axis indicates that it summarizes only 7.581% of the variability, and the eigenvalues for the first 10 axes summarize a cumulative variability of 42.950% (Table 5). Nonetheless, Axis 1 identifies the most important source of variability and distinctly separates the kerogen and +180 µm fractions (Figure 4). Eigenvalues and variable scores for the samples and for the taxa are recorded in Table 5. Figure 5 shows Axes 1 and 3 because the dispersion of the data on Axis 3 allows the sample distribution on Axis 1 to be seen with less overprinting of data points and labels. The kerogen samples are much more clustered on Axis 1 and 2 than the +180 µm fraction.

Table 5 shows the ordination of samples and taxa on Axis 1. Amongst the samples, Axis 1 separates the +180 µm fraction, that dominates the negative scores, from the kerogen, that dominates the positive scores. Only a few samples are interfiled in the low positive values of Axis 1. This ordination on Axis 1, having the highest eigenvalue and percentage of explained variability indicates that the difference between the +180 µm and the kerogen fractions is the single most important source of variability in the data set, although the actual explained variability is quite low. There is no apparent secondary order to the sample depths in Table 4, other than the separation of the two fractions, so no further interpretations of the pattern of recycling are evident.

The right columns of Table 5 show the Axis 1 scores of the taxa included in the analyses. These scores show the taxa that influence the ordination of the samples. Many taxa, recorded generically, are long-ranging and of little utility in discerning the age of recycled material. Other taxa have sufficiently limited stratigraphic distributions that they argue for recycling into younger strata, as the strata penetrated are of Late Eocene or younger age (White, 2009).

There are cautions associated with the variable scores. *Kurtzipites* which occurs in “513.66" m and 690 m, has an intermediate score of 1.186 on Axis 1. This score is due to the fact that sample 513.66 was eliminated from the analysis as an outlier, due to its very limited species list. In sample 690 m it is eroded and flagged as a questionable identification.

Some taxa are clearly recycled, even when identified on a generic basis. These taxa tend to be clustered on the negative end of Axis 1, in the +180 μm fraction. Those with Cretaceous (and perhaps Paleocene) distributions provide certain evidence of recycling. *Distaltriangulisporites* occurs in the Middle and Late Albian (Singh, 1971, 1983) ranging up to at least the Campanian (Payenberg et al., 2002). *Azonia* has an age range of ?Coniacian to Late Maastrichtian. *Cranwellia* has a late Campanian to Paleocene age range, and *Wodehouseia* ranges through the late Maastrichtian and Paleocene (Nichols and Sweet, 1993). *Hazaria sheopiariae* Srivastava 1971 occurs in the Campanian and Maastrichtian ages in Alberta (Srivastava, 1971; Jansonius and Hills, 1977; Payenberg et al., 2002), and in the Paleocene (see discussion in Parsons, 2000, p. 451). On the other hand, the presence of *Classopollis classoides* at the positive end of the Axis 1 eigenvectors cautions that the interpretation of this scale as a recycled/in situ continuum may be too simple. It is dominantly a Mesozoic taxon that does occur rarely in the Paleocene (Song et al., 1999), but seems out of place at the end of a continuum dominated by typical Neogene taxa. Nonetheless, the continuum seems to form the major pattern from older to younger taxa.

Other taxa have ranges in the Paleocene to Eocene. For these it is difficult to know if it is correct to interpret an occurrence as recycled, or as constituting a legitimate occurrence within its stratigraphic range. For example, in the Caribou Hills sections, *Triatriopollenites granilabratus* occurs in the zones CHE1 (L. Paleocene) to lower 4b (E. to M. and ?L. Eocene) (Parsons, 2000). [White (2009) has argued that the uppermost portion of CHE4b may be of Late Eocene age.] *Triatriopollenites pulcher* occurs in zones CHE3 (E. to M. Eocene) to 4c (Late Eocene/?Oligocene); recycling is considered possible to explain late occurrences of taxa in zone CHE4c (Parsons, 2000). Thus, *T. granilabratus* has a Late Paleocene and Early to Middle Eocene age range, and *T. pulcher* has an Early to Middle Eocene age range with questionable occurrences in the ?Late Eocene to Oligocene. The dominant time of occurrence of these *Triatriopollenites* species, as recorded by Parsons (2000), is Late Paleocene and Early to Middle Eocene. Thus, they are most probably recycled in the Mallik 5L-38 well samples reported here, but a range extension can not be excluded. A definitive answer may await the accumulation of much more regional palynostratigraphic data.

Pistillipollenites macgregorii has long been considered a reliable Late Paleocene to Middle Eocene biostratigraphic marker (Rouse, 1977), although its occurrence in the Mallik 2L-38 well and in the Caribou Hills zone CHE4c has caused White (2009) to argue that its age ranges upwards into the Late Eocene, a fact affirmed by its presence in the coals in Mallik 5L-38 (below).

Some biostratigraphic indicator taxa found in the +180 µm fraction were excluded from Correspondence Analysis because they occurred only once. *Aquilapollenites* spp. are present in Assemblages 3 to 10, of ?Coniacian-Santonian to Late Maastrichtian age in the Bonnet Plume and Brackett basins, Yukon and Northwest territories (Nichols and Sweet, 1993). *Callistopollenites* sp. is of Maastrichtian - Danian age (Jansonius and Hills,1977, Card 359). *Singularia sp.* could be from the Late Campanian to Maastrichtian transition, but it might also be a relic species which has come from a higher stratigraphic level (A.R. Sweet, pers. comm., 18 May 2004). Tricolpate type H of Parsons 2000 ranges from upper CHE3 to CHE4c of Early to Middle Eocene and Late Eocene or ?Oligocene age (Parsons, 2000). Triporate type D of Parsons 2000 occurs in CHE3 to CHE4b of Early to Middle Eocene age (Parsons, 2000).

In summary, it has been shown above that +180 µm and kerogen fractions of the organic matter have different assemblages, and those differences can be attributed - at least in part - to different proportions of recycled palynomorphs. Cretaceous palynomorphs are easily identified as recycled, but interpretation of Paleogene palynomorphs as recycled or contemporaneous is fraught with uncertainty. The Correspondence Analysis supports the original intent to analyse kerogen, as that fraction is probably less influenced by well preserved recycled palynomorphs.

It remains an unresolved question whether the separation of organic fractions of a sample, discussed above, and the following sample preparation recommendations, are appropriate for all stratigraphic levels in the Beaufort-Mackenzie Basin. Further work is required.

Sample processing considerations and recommendations

It is a convenient ‘shorthand’ assumption that the palynomorphs in the +180 µm fraction are recycled from significantly older rocks, although that is a too-simple assumption. A floodplain peat could be retained in the +180 µm fraction, but really be representing the contemporaneous portion of the palynomorphs. Conversely, the presence of palynomorphs in the kerogen fraction does not indicate that they are necessarily palynomorphs from plants living penecontemporaneously with sedimentation. Although a significant proportion of recycled palynomorphs in the kerogen may be detectable by taxonomy, colour and degree of preservation, there is surely also a recycled fraction that is undetectable.

Although kerogen carries a higher proportion of contemporaneous palynomorphs, the preparations are difficult to analyse because of the low concentration of palynomorphs. Improving palynomorph abundance and concentration in the kerogen fraction would be an important contribution to biostratigraphic interpretation by improving the recovery of the taxonomic diversity of the samples.

The following recommendations are made to improve the palynomorph preparation quality and interpretability.

1. Process samples larger than 13 to 20 g to kerogen.

2. Acetolysis results in improvement in both palynomorph concentration and in taxonomic determination because it removes fine organic detritus in the residue that adheres to, and obscures details of the palynomorphs. Improved visibility is a more significant benefit to palynology than loss of fine colour details. Gross differences in colour are of most value in determining recycling, and they are evident in spite of darkening by acetolysis. Smaller differences of colour are more ambiguous and of much less value in determining recycling.
3. Avoid strong oxidation of the sample to exclude palynomorphs transported in organic clasts which have a higher likelihood of being recycled. The +180 μm nominal fraction found on the screen should be retained and oxidized, and inspection will likely reveal well preserved palynomorphs that may give evidence of the age of recycled material. It should be investigated whether light oxidation with Javex can equally improve concentration and clean the palynomorphs, without releasing recycled palynomorphs or unduly altering colour.

Age and geological source of recycled taxa in Mallik 5L-38

Figure 6 shows the stratigraphic distribution of taxa identified as recycled, plus protists and unknown and undeterminable palynomorphs. Table 6 shows by sample, the age implication of selected taxa which are likely recycled, for which reasonable taxonomic certainty is possible and for which one can provide useful age constraints. The ages cited, where possible, emphasize stratigraphic ranges in northern North American palynostratigraphy, and are given chronological values following the International Commission on Stratigraphy time chart (Gradstein et al., 2004). Taxa listed in Table 6 represent a relatively small subset of all of the palynomorphs which are thought to be recycled, but are the palynomorphs that are distinctive and most likely to improve knowledge of recycling.

Figure 7 shows the potential ages of the recycled taxa by sample in which they occur, drawn from Table 6. More than one recycled taxon may be plotted by sample. Samples in green are the +180 μm fraction, and in blue, are the kerogen fraction. For plot separation, the +180 fractions are plotted 3.66 m below their true depth, but bars have been separated for visibility. The bar drawn for each taxon represents the broad range of ages from which a recycled taxon could be drawn, rather than indicating recycling from all the formations within that age range. The toned rectangle indicates the expected age of the sediment (White, 2009; and herein), showing the difficulty of separating recycling from range extensions. Long-ranging taxa in Figure 7 are *Classopollis classoides* and *Vitreisporites pallidus* that are dominantly Mesozoic taxa but may occur in the Tertiary. The genus *Classopollis* has a stratigraphic range up to the Eocene (Pocock and Jansonius, 1961) and *Vitreispories pallidus* may occur as an authochthonous element in the Danian (Krutzsch, 1967b).

The upper 450 m of the well (Figure 7), which has the highest proportion of recycled taxa, is the interval in which preservation is so poor that good fossil evidence for the ages of rocks being eroded and redeposited is not obtainable. At and below 440 m, the quality of preservation improves. At and below 450 m, separate kerogen and +180 μm analyses were completed per sample. From there to 900 m, the age of recycled material is constrained to being from the late Cretaceous to the Paleogene.

From 420 to the 900 m there is a regular occurrence of taxa which are probably of Cretaceous - dominantly Campanian or Maastrichtian - age; e.g. *Aquilapollenites* spp., *Azonia* spp., *Hazaria sheopiariae, Wodehouseia* spp. However, some of these genera have species that range into the Paleocene.

In addition to probable Cretaceous taxa, below 540 m occur taxa whose stratigraphic ranges are dominantly Cenozoic, including *Paraalnipollenites alterniporus* (also of latest Maastrichtian age; Nichols and Sweet, 1993), *Pistillipollenites macgregorii* and *Momipites wyomingensis*, *Triatriopollenites pulcher and T. granilabratus (Rouse*, 1977; Parsons 2000). Triporate type D of Parsons 2000 and Tricolpate type H of Parsons 2000 were recorded in the Caribou Hills sections (Parsons, 2000) but their stratigraphic ranges are not well known.

Between 650 and 730 m, chiefly in the +180 µm fraction, occur several long ranging Cretaceous taxa, including *Distaltriangulisporites* spp., *Vitreisporites pallidus, Appendicisporites* sp. and *Tigrisporites* sp. In this interval also occur the dinoflagellates *Chatangiella ditissima* (623.66 and 653.66 m) and *C. verrucosa* (633.66 m). *Chatangiella ditissima* is of late Cenomanian to Campanian age in the Beaufort-Mackenzie area (McIntyre, 1996). *Chatangiella verrucosa* is Coniacian to Late Campanian in age (Williams et al., 1993). The reduced incidence of palynomorphs of approximate Santonian and younger age in the 650 to 680 m interval, where the longer ranging Cretaceous taxa dominate, suggests an actual change in the source of recycled palynomorphs. The occurrence of marine fossils suggests a change in source to marine rocks, such as the Santonian to Campanian Smoking Hills and the Maastrichtian Tent Island formations (Lane and Dietrich, 1996). In marine rocks, continental palynomorphs would be less abundant, and less likely to be found as recycled palynomorphs.

Lane and Dietrich (1995) concluded that, from the Eocene to the Pleistocene, the source area for Beaufort-Mackenzie Basin sediment was the northern Cordillera, which includes the Ogilvie and Richardson Mountains, the Porcupine River drainage and the northeastern Brooks Range. The paleo-Porcupine River deposited sediment near the modern Mackenzie Delta. Thus, the source of palynomorphs is likely to be in the paleo-Porcupine River drainage area. Within this paleo-drainage are extensive outcrops of Cretaceous rock, and much more limited outcrops of Jurassic rock (Norris, 1984). For the Campanian-Maastrichtian interval, most of the identifiable recycled palynomorphs were derived from the Tent Island Formation.

INTERPRETATION OF THE MALLIK 5L-38 WELL BY QUANTITATIVE ANALYSIS OF THE KEROGEN FRACTION

The comparison and discussion above has shown that the +180 µm and kerogen fractions of cuttings represent different aspects of the palynological signal from the Mallik 5L-38 well, and that the +180 µm fraction can be interpreted to have a significant component of recycled palynomorphs. The following analysis and discussion is to determine if a coherent and credible palynological signal can be extracted from the quantitative data collected from the kerogen slides. Estimates of concentration of palynomorphs/g of sediment are used to assess the existence of discrete stratigraphic units. Identified palynomorphs, plus recycled and unknown and undeterminable palynomorphs and well caliper logs are combined to interpret depositional and environmental history recorded in the sedimentary column.

Concentration

Palynomorph concentration estimates are used here as a stratigraphic tool, both to separate sedimentary packages and to demonstrate that there are non-random patterns associated with the deposition of this sedimentary stack. Palynomorph concentration is a function of both the ecosystem productivity of palynomorphs and of the sedimentation rate; low productivity and/or high sedimentation rate result in low concentrations. It is not possible to separate these two factors without calculating the palynomorph accumulation rate - a calculation possible only where an independent chronometry is possible, such as supplied by radiocarbon dating for late Quaternary sediments; hence concentration is used. Coherent patterns of palynomorph concentration in sediment is evidence that one is seeing interpretable environmental or biological drivers of the fossil content of the rocks (White, 2009).

The concentration of palynomorphs per gram of sediment can be calculated only for the clastic portion of the sediment from which palynomorphs could be released without oxidation (Figure 8) because the exotic spike *Lycopodium* was retained in this kerogen fraction (above). Concentration estimates are inherently “noisy” when the count of the exotic spike and fossil palynomorphs is low, and are best interpreted as trends.

Concentration estimates are not possible for the portion of organic matter that was retained on the +180 µm screen in samples from 450 to 900 m because exotic spike *Lycopodium* spores were not transferred to this fraction during processing. The +180 µm fraction constitutes a very small portion of the sample weight, but perhaps a larger fraction of the organic matter in the sample. However, there is no way to estimate the fractional weight with the data available. As discussed above, the +180 µm fraction presents many recycled palynomorphs, and this recycled portion of the palynoflora is not relevant to interpretation of the age or depositional environment of the clastic portion of the sediment, other than establishing a maximum age.

Before making conclusions about concentration, it is necessary to consider whether the modifications in processing made during the laboratory preparation had any effect on the concentration estimates. Due to the increasing difficulty in getting workable palynomorph concentrations as analysis moved down-hole, at 570 m it was decided to acetolyse the remaining kerogen residues and mount new slides; this procedure was later extended to samples 550 and 560 m.

Double counts and intra-sample comparisons were made for samples from 580 to 630 m (Table 3). The acetolysed residue from three samples, 580, 590 and 600 m were compared with the kerogen only residues (Table 3). The results are:

1. Acetolysis increased the palynomorph count by ~50% to ~300% and increased the *Lycopodium* spike count about in proportion, which would have had little effect on concentration estimates.
2. Increased counts resulting from acetolysis yielded more taxa, 20 vs. 12 at 580 m., 18 vs. 15 at 590 m and 25 vs. 12 at 600 m.
3. The Pinaceae/T-C-T (including *Inaperturosporites dubius* as a T-C-T) ratio is very different at 580 m (1:4 for kerogen vs. 1:1 for acetolysis) and 600 m, (1:1 for kerogen vs. 3:1 for acetolysis) but is similar at 590, (6:4 for acetolysis vs. 7:4 for kerogen). Considering the low counts involved (Table 3), these ratio differences are probably not statistically significant.
4. Determination of categories such as the Pinaceae and triporates was facilitated by the removal of micrometer-scale organic detritus adhering to the palynomorphs.

Acetolysis thus probably changed results in some aspects of the record, especially diversity, but improving palynomorph recovery was a necessity for continuing the analysis. The group percentages and concentration diagram (Figure 8) shows no abrupt and systematic difference between samples above and below 545 m other than the situation that caused the modification in processing, the decline in palynomorph productivity. Likewise, the terrestrial percentage pollen diagram (Figure 9) does not show abrupt, systematic differences above and below 545 m, except that the “Count Sum Terrestrial Palynomorphs” shows higher sums below 545 m. Lower values occur in “Sum Unknowns and Undeterminables” (Figure 8) below 545 m, but this is apparently also part of a longer term trend. On balance, the change to acetolysis treatment of the kerogen slides was beneficial, improving concentration on the slides and cleaning specimens, improving counts and increasing species diversity per slide, and allowing information to be recovered from otherwise intractable samples.

The difficulty of obtaining high counts of palynomorphs in the kerogen is evident from Figure 8. Only rarely are concentrations above 2000 palynomorphs/gram, in itself a very low concentration; pollen-rich sediment would have a concentration between one and two orders of magnitude higher. However, there are patterns even within these low concentrations.

Concentration values in Figure 8 can be compared with the drilling history notes in Table 1 and the caliper log (Figure 2, 8). The interval from 116 to 320 m has extensive hole erosion. Except for the high concentration estimate at 110 m (attributable to statistical error associated with very low counts of exotic spike and palynomorphs), concentration in this interval is low, with three barren intervals, suggesting low pollen productivity and/or rapid sedimentation. Figures 2 and 8 show the interval 320 to 560 m as having considerable erosion with some non-eroded sections. In this interval, the palynomorph concentration rises somewhat above the overlying interval, with an individual peak at 380 m and a decline at 470 m. The trend in concentration from 500 to 570 m is decline. The interval from 560 top 650 m has minor erosion, and the pollen concentrations are uniformly low.

Palynomorph concentrations were calculated previously for Mallik 2L-38, located only about 100 m from the 5L-38 well (White, 2009, Figure 6). The 5L-38 analysis overlaps the interval from 670 to 886.3 m that was studied in 2L-38. The concentrations for this interval in 2L-38 are in the range of 1000 to 1100 grains/g sediment, in good agreement with the estimates for 5L-38 ranging around 800 to 1200 grains/g sediment. Some of the minor trends are different in 2L-38, particularly the slightly higher values, between 1200 and 1800 grains/g sediment in the 670 - 680 m and 740 - 800 m intervals, and the 710 m and 860 - 870 m peaks in 5L-28. These are small differences in concentration estimates, but might also reflect different beds penetrated by adjacent wells. The good agreement between the concentration values in the overlapping portion of the 2L-38 and 5L-38 wells is a useful corroboration of the technique.

The reasonable agreement of concentration values with caliper log measurements and palynomorph percentages reinforces the assumption that the biostratigraphic signal is patterned, not random. The next step is to identify the patterns in the taxonomic data.

Stratigraphic discontinuities indicated by the Sum of Recycled Palynomorphs, the Sum of Unknown and Undeterminable Palynomorphs, and Caliper Logs

Percentages of palynomorph groups (Figure 8) particularly the Sum of Unknown and Undeterminable Palynomorphs, and the Sum of Recycled Palynomorphs, have long-term trends that shed some light on stratigraphy and depositional environment. Interpretation follows discussion of the patterns.

The Sum of Recycled Palynomorphs comprises the palynomorphs that are known to be recycled, either by taxonomic identification or by high thermal maturity. On a broad scale this sum shows a variable but general rising trend from 900 m to 340 m, with stepped increases at 700 m and another at about 340 m. According to the caliper log (Figures 2 and 8, Table 1) at and below 340 m the hole was either close to nominal gauge or washouts are within the measuring span of the caliper tool. Above 340 the hole is extensively caved, excepting a thin resistant bed at 315 m. The sudden increase of the Sum of Recycled Palynomorphs within poorly consolidated sediment argues that a great portion of the organic matter above 340 m has been recycled and that the sediment is relatively young.

The Sum of Unknown and Undeterminable Palynomorphs comprises the abundant palynomorphs that are too degraded for useful identification and are recycled from older rocks, plus a very small proportion of unknown taxa. There is no clear trend in Sum Unknowns and Undeterminables below 550 m. Going stratigraphically upwards, a stepped increase begins at 550 m, and a rising trend begins about 450 m, increasing to a broad peak between 380 and 280 m, where this Sum comprises the dominant portion of the Palynomorph Sum - even greater than 50 %. By the closure effect of percentages, the dominance of the Sum of Unknowns and Undeterminables may significantly suppress other percentages.

The fungi are interpreted to represent organic matter decay organisms in soil. The Sum Fungi curve is generally less than 10% of the Sum Palynomorphs, but, in spite of the percentage closure effect, shows a similar rising trend above 450 m with a group of high values between 330 and 280 m, and subsequent high but variable values. Hence, Sum Fungi shows some patterns similar to Sum Unknowns and Undeterminable. These two curves suggest a gradual increase in regional erosion from 450 m to 360 m. An increase in sedimentation rate would likely be a result of increased erosion, diluting palynomorph concentration. Consistent with this, the Palynomorph concentration curve has low values between 340 and 250 m.

Above 340 m the section is unconsolidated and greatly influenced by sediment recycling, although useful biostratigraphic indicators do occur. Both the Sum of Unknowns and Undeterminables and Sum of Recycled Palynomorphs show similar general declining trends in the 250 to 200 m interval, suggesting that there is some interpretation possible, other than recycling, for the data in this uppermost interval.

The sums of Recycled Palynomorphs, Unknowns and Undeterminables and Fungi, considered along with lithostratigraphic and organic fraction data, corroborate stratigraphic discontinuities at 445 and 340 m. The 445 m point, below which the +180 μm fraction organic fraction could be separated during treatment (see above), is probably the point at which regional erosional processes became sufficiently energetic that the recycled organic matter was so comminuted during erosion that it can not be separated from the contemporaneous component.

There are relatively few dominant trends in other Sums for which an interpretation is apparent. The Sum Ferns and Allies, Sum Gymnosperms and Sum Angiosperms are low between 380 and 280 m, possibly an effect of climate and of landscape erosion, and of percentage closure.

There appears to be an inverse relationship between the Sum Protists and Annelids and the Sum Fungi in the 340 to 260 m interval, with the former being virtually absent and the latter showing increased numbers. Most of the Sum Protists and Annelids comprise a few palynomorphs of possible marine to freshwater environmental tolerance, including dinoflagellates, a foraminiferal lining, a scolecodont, and algae. Placing taxa in this category or in the Recycled category was not clear-cut. This interval, with high values in Sum Recycled Palynomorphs and Sum Unknowns and Undeterminables, is an intense recycling episode, and likely represents energetic terrestrial erosion.

Issues concerning correlation and age determination

Correlation of the age for the sediments studied, as well as the paleoclimatic and paleoenvironment interpretation, requires comparison to other studies. However, there are caveats associated with comparison to studies that may have been completed by different methods, a point emphasized by the preceding discussion of the influence of preparation techniques. Consideration must be given to the comparability of Mallik 2L-38 and 5L-38 results and the comparability of those two studies with other studies in the Beaufort-Mackenzie Basin, prior to correlation and age discussions. Also, directly bearing on the age and correlation issue is how the Kugmallit Formation is currently recognized palynologically.

Comparability of Mallik 5L-38 and 2L-38 samples

Studies of both the Mallik 2L-38 and 5L-38 wells are quantitative, and to a large degree the data are on an equal footing. However, there are residual uncertainties about the effect of processing on the representation of recycled taxa.

The processing technique used for Mallik 5L-38 excluded from the kerogen preparation the +180 µm fraction which carries many recycled palynomorphs. It was argued to be unlikely that palynomorphs typical of that fraction were released into pollen preparations for the 2L-38 well, in spite of the use of ultrasonic screening, light Javex bleaching and base neutralization because it required strong, hot Schulze solution oxidation to release the +180 µm fraction palynomorphs. However, this question of preparation technique and recycled palynomorphs will be raised again in the discussion of pollen ratios as climate proxies (below).

Problems in correlation between Mallik and other studies

Correlation between a quantitative study, that has a relatively high sample density, and other studies entails several problems.

Sedimentation rate and sample density

Both differential sedimentation rates and the intensity of sampling complicate the sequence of first appearance and last appearance datums. Both a high sedimentation rate, and/or an intensive sampling interval will separate appearance datums which might otherwise be recorded as contemporaneous in slower sedimentation and/or a coarser sampling interval. Low sedimentation rate marine environments will especially make events appear contemporaneous which are separable in a higher sedimentation rate environment, the sampling interval being equal.

Quantitative vs. presence-absence records

In comparison between quantitative data and presence/absence data it is necessary to be mindful of the representation of the underlying distributions by these data types. One assumes that the underlying fossil distribution is a curve, bell-shaped or otherwise. Palynology is the process of sampling that distribution. A fully quantitative palynological record (if complete) should approximate the shape and limits of the underlying distribution. A presence/absence record will approximate the underlying distribution to the degree that the area of maximum abundance - central portion of the curve - will be recorded as a more-or-less continuous series of presences, and in the more distal portions of the distribution, where the fossil is rarer, the palynological representation will be an increasingly discontinuous series of occurrences (see discussion in White and Jessop, 2002).

It is difficult to define the limits of a taxon's range by presence/absence or quantitative analysis, although the latter is superior. The underlying distribution curve is asymptotic, so on statistical grounds one can not assign discrete limits. Moreover, the plants producing the pollen in the source region are unlikely to suddenly disappear in the face of gradual environmental change, but rather to become progressively rarer in the immediate landscape, withdrawing to the most favourable habitats, perhaps reproducing vegetatively, and eventually withdrawing to more distant, favourable areas. They are then truly absent in the region, but in the case of anemophilous taxa, airborne pollen may occasionally arrive on winds and enter the sedimentary environment, providing a very discontinuous record of the taxa. For both reasons, is it difficult to conclusively define a pollen or spore's chronostratigraphic limits.

Rate of environmental change and definition of intervals

The rate of environmental change determines the shape of the distribution curve. Sudden truncations may indicate sudden environmental change, but given that continental sedimentary records likely have more time missing than recorded, sudden truncation may indicate unconformities of varying magnitudes.

The practice of biostratigraphy requires the definition of stratigraphic intervals, but it is difficult to subdivide sequences in which gradual changes occur in many variables over long intervals of time, and inflection points are not the same for all variables. If some variables undergo more or less discrete changes and others change over longer intervals, it is practical to arrange the subdivision to recognize the discrete changes, at the expense of a poorer fit with the more gradual changes. Some of the changes noted at zone boundaries herein do not coincide perfectly with the indicated stratigraphic level. The choice of stratigraphic divisions implies a weighting of the significance of variables, which hindsight may show to have not been appropriate. Zonations made by various workers can result from differing intuitive weighting of data.

The Oligocene in other Beaufort-Mackenzie wells and comparison with Mallik 5L-38

Patterns derived from Mallik wells should be verified by results from other Beaufort/Mackenzie wells, but one must be mindful of problems in such comparisons. Mallik 5L-38 has a 5 m cutting sample interval, versus the typical 30 m industrial cutting sample interval. Moreover, this studies research objectives required quantitative data versus the semi-quantitative or presence/absence data from other studies. Comparison with other wells is complicated by the differentially expression of sedimentary packages and unconformities, and probably by differential representation of palynomorphs depending on their continental vs. marine position.

Processing

Processing differences between studies must have influenced the representation of recycled palynomorphs. If the +180 μm fraction, separately treated in this study, were oxidized with the sample, the palynomorphs in that fraction would be released into the preparation and would contribute significantly to the identifiable portion of the sample, or might even dominate the assemblage in intervals where recycling is common. Paradoxically, the samples would appear to be palynologically richer and more workable.

The Nuktak C-22 and Adgo F-28 wells (Norris, 1986, 1997) appear to have been processed by oxidation, and other wells were probably similar. In Nuktak C-22, Norris (1986) notes that samples were macerated using standard oxidation at the Institute of Sedimentary and Petroleum Geology (I.S.P.G., now G.S.C. - Calgary). Johnson (n.d.) does not indicate that preliminary screen removal of a coarse fraction was a standard procedure for the I.S.P.G. Palynology Laboratory in the 1970's. R. Kalgutkar, who began working in the I.S.P.G. Palynology Laboratory in 1980, indicated that a +150 µm screening was standard procedure <u>after</u> oxidation (personal communication, 19 July 2005). Thus, any recycled material in the +180 µm fraction would have been released into the sample if oxidation was complete. Nuktak C-22 slides were processed in 1979.

Adgo F-28 samples were not processed in the I.S.P.G. laboratory but were processed using “standard acid oxidation procedures” (Norris, 1997). Thus, the conclusion drawn for Nuktak C-22 likely applies to Adgo F-28.

This recognition in this study that processing may have released recycled palynomorphs into the residues in other studies does not necessarily invalidate the analytic results of those other studies. First, the taxa recovered in this study from the kerogen should be present in other wells, plus potentially recycled taxa. Second, this study has not defined the portion of the Beaufort-Mackenzie stratigraphic column to which this fractional separation problem applies - it may be limited, and if so, is most likely limited to the upper Cenozoic section. Third, the Mallik wells are fluvial/deltaic, whereas the other wells are offshore, and may not be as influenced by the +180 µm fraction problem. These stratigraphic and geographic distribution questions regarding recycled organic matter need to be kept in mind and constrained by further work.

Significance of recognition of Kugmallit Formation in Adgo F-28

In Adgo F-28, Norris (1997) indicated that the lower boundary of the *Tsugaepollenites* Zone is an erosional contact with the Eocene at 2700 ft (823 m), but subsequently McNeil (in White, 2009) identified a thin intervening interval of Kugmallit Formation between 2800 and 3000 ft (853.4 and 914.4 m). If there is an erosional event at 2700 ft, it would suggest that it is the lower portion of the Kugmallit that is represented. Recognition of this unit transfers many palynostratigraphic LADs from the Eocene into the Oligocene, probably the Early Oligocene**.** The LADs of 15 taxa now are in the Kugmallit Formation, including pteridophyte and angiosperm taxa of interest here: *Caryapollenites veripites*, *Momipites waltmanensis*, *Retitriletes* sp. cf. *R. novomexicanus*, *Verrucatosporites favus*, *Integricorpus* sp. A, *Montanapollis globosiporosus*, *Aceripollenites tener*, *Caryapollenites inelegans*, and *Momipites wyomingensis*. In particular, “*Integricorpus* sp. A” a distinctive species, ranges into the Oligocene instead of having a top in the Richards. It was also found in Mallik 2L-38 at 936.32, 946.21, and 950.11 m. [White (2009) has suggested the use of the name *Integricorpus* sp. cf. *I. reticulatus*, instead of “*Integricorpus* sp. A” to conform with Parson’s usage in her Caribou Hills study (2000). *“Integricorpus* sp. A” nominally occurs in Nuktak C-22 (Norris, 1986) but, on re-examination, was determined by White (2009) to be a different species from "*Integricorpus* sp. A" mentioned above and the informal name *Parviprojectus* sp. A of Rouse 1977 was suggested. Thus, *Integricorpus* sp. cf. *I. reticulatus* does not occur in Nuktak C-22.]

Tsuga and *Baculatisporites* are common in the upper Kugmallit Formation (the Arnak Member), in the lower Mackenzie Bay Formation in Nuktak C-22 (Norris, 1986) and in the Mackenzie Bay in Adgo F-28 (Norris, 1997). The recognition of the Kugmallit in the Adgo F-27 well (McNeil, in White, in press) improves correlation between these two wells by putting some of the portion of most regular occurrence of their range into the Kugmallit, but they still range into the upper Mackenzie Bay Formation.

Palynological definition of the top of the Kugmallit Formation in Nuktak C-22 and Adgo F-28

Norris' (1986) analysis of the Nuktak C-22 well provides a palynologically well-described subsurface section for the Oligocene (Norris, 1986). The Nuktak C-22 well has a 3645 ft-thick (1111m) Kugmallit section (Oligocene, 6920 to 3275 ft, 2109.2 to 998.2 m) overlain by a thinner, 1457 ft (444 m) Mackenzie Bay section (Miocene, 3275 to 1818 ft, 998.2 to 554.1 m; Dixon, 1990). The Kugmallit is divided into the lower Ivik and upper Arnak members. Comparatively, Adgo F-28 has a thin, 200 ft (61 m) Kugmallit section (3000 to 2800 ft, 914.4 m to 853.4 m) and a 1100 ft-thick (335 m) Mackenzie Bay section (2800 to 1700 ft, 853.4 to 518.2 m) of similar thickness to Nuktak C-22. The 200 foot (61 m) thick Kugmallit section was only recognized in a re-examination of the well (McNeil, in White 2009), and subdivided from what was previously considered to be the upper Richards Sequence by Norris (1997).

For applied biostratigraphy with drill bit cuttings, the palynological Last Appearance Datums (LADs) in the Kugmallit Formation are important. Nineteen taxa have LADs in Nuktak C-22 within the 3399 to 3000 ft (1036 to 853.4 m) level in the upper Arnak Member (Norris, 1986). Fifteen taxa have LADs within the thin, 200 foot (60.96 m) Kugmallit Formation in the Adgo F-28 well (Norris, 1997; McNeil, in White, 2009). So by biostratigraphic discontinuity, the observed top of the Kugmallit Formation appears distinct. Yet there is very limited commonality of taxa between the two wells at the top of the Kugmallit.

Table 7 lists taxa that have LADs at, or adjacent to the top of the Kugmallit Formation in Nuktak C-22 and Adgo F-27. The listing of adjacent taxa is to allow for some uncertainty in the pick of the formational boundary while assessing the degree of flora change at this transition. The dark line represents the picked boundary between the Kugmallit and the overlying Mackenzie Bay formation. Taxa in bold face are those that occur in both wells near this boundary. Fungal hypae type G is distinct, but *Tricolpites hains* is less so, and neither were recorded in the Mallik 2L and 5L-38 studies. *Dyadosporites oblongatus* and *Dyadosporites* sp. A Norris are closely related and would be called *Dicellaesporites* in this Mallik 5L-38 study, where it is broadly distributed. *Intratriporopollenties crassipites* and *I. minimus* are closely related and would be called *Tilia*-type herein. *I. crassipites* has a LAD higher in the Mackenzie Bay Sequence in Adgo F-28. A total of 40 taxa have LADS ±200 ft of the boundary in Nuktak C-22 and Adgo F-27, yet only four

(10%) are in common or closely related. Thus, the palynological definition of this event is not clear.

Comparison of long-ranging taxa in Nuktak C-22 and Mallik 5L-38

Stratigraphic tops (or Last Appearance Datums) are nominally discrete events, but they are prone to statistical variability. Moreover, any taxon which has an interrupted distribution due to climatic or environmental changes can exhibit several apparent tops within its range. This can give spurious correlations when working with incomplete sections. Alternatively, correlation arguments can be made based on variations in the distribution of long-ranging taxa, although it is hard to define discrete events. In spite of the pitfalls, such arguments may be helpful in Beaufort-Mackenzie palynology, and are explored below.

Unlike stratigraphic tops, the regular occurrence of a taxon does not provide a discrete point of correlation, but it can characterize a stratigraphic unit. It is effectively an argument based on statistical central tendency rather than on variability (although these are probably all multi-modal distributions). In Nuktak C-22 (Norris, 1986), several taxa occur regularly in the Arnak Member but range upwards into the lower Mackenzie Bay, including *Ulmipollenites undulosus*, *Baculatisporites crassiprimarius*, *B. quintus*, *Tsugaepollenites viridifluminipites*, and *Ericipites compactipollinatus*. There are no exact taxonomic equivalents in this analysis of the Mallik wells, but these taxa would be included in the *Ulmus*-type, *Baculatisporites spp., Tsuga canadensis*-type or *Tsuga* sp., and Ericales, respectively. These taxa occur commonly in the 850 to 700 m interval in Mallik 5L-38 (excepting *Ulmus* -type, which is more intermittent) suggest that interval to be of late Oligocene age, with more intermittent occurrences in the 700 to 550 m interval, thought to be of Early Miocene age. Above 550 m, and certainly above 445 m, increase in regional erosion makes the record of occurrences of Ericales more dubious.

Zonation, correlation and age and environment

This discussion of correlation seeks tie points to other regional wells or sections, evaluates the reliability of the correlation, and attempts to interpolate between tie points. The caveats, discussed above, apply to the reasoning presented below. Similarities between this zonation and that of other studies of gas and organic matter are noted.

The following discussion draws on: Figure 1, the study location map; Figure 8, the percentages of palynomorph groups calculated on the sum of all palynomorphs; Figure 9, the percentage of terrestrial palynomorphs, calculated on the sum of terrestrial palynomorphs; and Figure 12, the palynological correlation of Late Eocene and younger strata in Mallik 5L-38 and 2L-38 wells to Beaufort-Mackenzie Basin wells and sections.

Interval 0 - 270 m

Although less so than the underlying stratigraphic interval, this interval has abundant Recycled and Unknown and Undeterminable palynomorphs, but is not devoid of useful information. *Artemisia* occurs at 270 and 260 m, and Onagraceae pollen at 220 m. The pollen and spore assemblage is sparse, consistent with a cool to cold environment. The percentage of *Picea*, a cool climate tree, is on average higher than in underlying intervals. The continued presence of T-C-T and *Inaperturosporites dubius* (probably T-C-T pollen) is probably due to recycling, as these genera are common in Cretaceous and Paleogene rocks. However, *Juniperus* is a member of the Cupressaceae, and is a modern indigenous plant tolerant of harsh edaphic and climatic conditions. *Juniperus* may have contributed to pollen in the T-C-T category.

Artemisia is the most distinctive marker in Mallik 5L-38 in the 0 to 270 m interval. *Artemisia,* and the apparent sparsity of vegetation, are consistent with a late Plio-Pleistocene age of 2.7 Ma or younger, after the onset of major Northern Hemisphere glaciation (Balco et al., 2005; White et al., 1999).

In Mallik 2L-28, core was recovered and analysed from the 110 to 118 m interval. It is interpreted to be of Late Pliocene-Pleistocene age, based on the palynomorph content of the core (White, 2009) and evidence of probable glaciation from underlying strata in the 5L-38 well.

There is no direct palynological basis for correlation of the 0 - 270 m interval to Nuktak C-22, although it must fall in part within the *Laevigatosporites* zone, Nuktak Formation and Iperk Sequence (Norris, 1986; McNeil and Birchard 1989; Dixon, 1990). Likewise, *Artemisia* was not identified in Adgo F-28 (Norris, 1997), but this interval would correlate to the upper *Chenopodipollis* and *Laevigatosporites* zones, Nuktak Formation and Iperk Sequence (Norris, 1997; McNeil in White, 2009).

Interval 270 - 340 m

This interval is impoverished of organic matter. The Palynomorph Concentration (Figure 8), Palynomorph Sum and Count Sum of Terrestrial Palynomorphs are very low (Figure 9), in spite of intensive slide scanning, so that percentages calculations have wide confidence limits. Nonetheless, there are significant features in this interval. *Alnus* and *Betula* pollen are generally absent while *Pinus, Picea* and Pinaceae Undifferentiated are uncommon, in spite of the fact that these taxa are both long-ranging and amongst the most common palynomorphs in the Neogene or Quaternary in northern Canada. *Sphagnum* is relatively abundant, suggesting that it formed a common vegetative cover. Fungal hyphae and *Papulosporonites* occur consistently and in peak values. Of the Sum Palynomorphs, Recycled Palynomorphs comprise 5 to 30%, and Unknowns and Undeterminables comprise 40 to 80% (Figure 8). This stratigraphic interval appears to have been deposited during a time of sparse vegetative soil cover when higher plants were poorly represented in the regional vegetation. Erosion was likely common, with recycling of palynomorphs and their corrosion during transport. The lowest concentration is in the 340 - 250 m interval, nearly coincident with a peak in the fungal palynomorph *Papulosporonites*.

In spite of the predominance of recycling in this interval, there are palynomorphs which are likely in place. The caliper log (Figure 2) shows that the hole is caved beyond the span of the logging tool, but there are resistant intervals at about 315 to 320 m, and from about 335 to 360 m, in which interval the hole is at gauge. *Shepherdia canadensis* and Chenopodiineae occur at 310 m. Both *Shepherdia canadensis* and Chenopodiineae are common Neogene/Quaternary shrub and herb taxa, consistent with a harsh environment. *Shepherdia canadensis* suggests nutrient poor conditions as it is a nitrogen fixer. The Chenopodiineae includes the herbaceous Chenopodiaceae and related Amaranthaceae. The Chenopodiaceae are halophytic (Heywood, 1978) so Chenopodiineae might indicate open vegetation on soils rich in salts.

It is noteable that the concentration of palynomorphs per gram of sediment is very low, about 1000 palynomorphs/g. Even were all these palynomorphs recycled (which they are not), this sparse quantity would be swamped by contemporaneous palynomorphs during a time of abundant vegetation productivity and low sedimentation. A cold climatic event causing a decline in vegetation productivity, with some glaciation and erosion, would be consistent with the palynological and stratigraphic evidence. If glaciation is the correct explanation, it does not necessarily imply a late Pleistocene glacial style of continental-scale ice coverage, but perhaps a more restricted glacial episode involving sites at high elevations.

This interval is identified by the quantitative traits in the sums of Recycled and of Unknown and Undeterminable taxa, and can not be correlated to non-quantitative studies. It likely correlates to the same published zones as the 0 - 270 m interval (above).

There are no stratigraphically restricted taxa in this interval that provide correlation or age evidence (Figure 12). Both *Shepherdia canadensis* and Chenopodiineae are longer ranging in the Cenozoic. *Chenopodipollis* sp. A, equivalent to the term Chenopodiineae used here, occurs in Nuktak C-22 (Norris, 1986) once at 5100 to 5200 ft (1554.8 to 1585 m) in the uppermost Ivik Member, and is somewhat more common between 2900 to 1200 ft (884 to 365.8 m) in the Mackenzie Bay and lower Nuktak Formations; hence its range in Nuktak C-22 precludes precise correlation. In Adgo F-28, Norris (1997) has named a *Chenopodipollis* zone after *Chenopodipollis nuktakensis*, but this taxon more likely belongs in the Caryophyllaceae, not the Chenopodiaceae or Amaranthaceae, and is not similar to the Chenopodiineae or *Chenopodipollis* sp. A. No other chenopods occur in Adgo F-28.

Deposition of eroded material was a dominant process in the strata between about 270 to 340 m. An explanation for erosion could be tectonism, but the proximity to the modern surface suggests that the cause was late Pliocene-Pleistocene glaciation (White et al., 1999; Duk-Rodkin et al., 2010; Duk-Rodkin and Barendregt, 2011). Glaciation could have intensely eroded regional bedrock and rapidly deposited fine-grained, poorly consolidated or ice-bonded sediment. This material would be highly prone to caving during drilling, even with chilled mud.

Dallimore et al. (1999) placed the base of the Iperk Sequence in Mallik 2L-38 at 346 m, based on log interpretation. This coincides remarkably with this palynological zonation of Mallik 5L-38.

Gas zonation

There is a correlation between the palynological zonation in Mallik 5L-38 and gas zones of Lorenson et al. (2005), where the 0 to 350 m interval is a zone of microbial hydrocarbon gas, with little to no thermogenic gas. Although the explanation is uncertain, it is worth noting this coincidence. The mechanism may have to do with both gas source and stratigraphic integrity.

Interval 340 - 700 m

From a palynostratigraphic perspective, it seems best to categorize this as one major unit. There are subdivisions within it but it is not readily divisible into subzones because variables do not change synchronously.

The upper boundary of this interval, 340 m, is in the interval of peak abundance of the Sum of Unknown and Underminable Palynomorphs, declines in the Sums of Angiosperms and in abundance or regular occurrence of *Alnus*, *Betula*, and Ericales. It is near the base of an interval of very low concentration of palynomorphs (Figures 8, 9).

At the base of this interval, 700 m, there is no identified lithostratigraphic change, being defined primarily by changes in the percentages of ferns and fern allies. It is the top of the regular occurrence of *Baculatisporites primarius crassiprimarius*, *Baculatisporites quintus* and *Baculatisporites* sp. (which occur sporadically up to 610 m). *Laevigatosporites* declines in percentage abundance, the Sum Fungi increases, and *Larix/Pseudotsuga* begin to have regular occurrences, compared to the underlying interval. The Sum of Recycled Palynomorphs (those identifiable), has a spike that marks a slow increase from the underlying interval, and the Count Sum of Terrestrial Palynomorphs is lower than in the underlying interval. This argues for some increase in regional erosion. Its gradual initiation may be indicative of a tectonic cause.

Within this 340 to 700 m interval, changes in the palynological record occur at 550 m depth, at the top of the sample to which acetolysis was applied to enhance the concentration of palynomorphs (see discussion above regarding processing). Above 550 m are small average increases in the T-C-T pollen, in Palynomorphs/g sediment, and in the Sum of Unknowns and Undeterminables. The increase in this latter sum may represent another increase in regional erosion. This is just above the top of *Tsuga canadensis*-type pollen (*Tsuga heterophylla*-type was not recorded in the kerogen of Mallik 5L-38, but occurs in adjacent strata at 690, 860, 890.71 and 900.63 m in Mallik 2L-38). *Tsuga* spp. occur rarely above this point. Within this 700 m to 550 m interval is the top of the sporadic occurrences of *Baculatisporites* spp., at 610 m.

At 445 m is the top of the interval in which the +180 µm fraction was separated during processing, and is also the beginning of the strong upward rise in the Sum of Unknowns and Undeterminables and Fungi, an increase in *Inapertisporites dubius* (therefore probably in T-C-T pollen) and a further increase in the concentration of palynomorphs/g sediment. This likely also represents accelerated regional erosion.

Both the palynological evidence and caliper log data for this 700 m to 340 m interval suggests increasing regional erosion. It may have culminated in a glacial event (above).

By the constraint of the super- and subjacent strata, this interval could fall in the age range of Miocene to perhaps Early Pliocene (Figure 12). If that time interval were fully recorded, one would expect evidence of the thermophile-rich assemblage characteristic of the Middle Miocene warm interval that is detected in Issungkak O-61 (White, 1989), and demonstrated in the Upper Ramparts Canyon and the Nenana coalfield of Alaska (White and Ager, 1994; Leopold and Liu, 1994; White et al., 1997, 1999). In the Ukalerk C-50 well (McNeil et al., 1982; Dixon, 1990) there appears to be a bimodal distribution of thermophiles, suggesting that the late Oligocene warm interval identified by Norris (1982, 1986) in the Arnak Member in Nuktak C-22, is also evinced in Ukalerk C-50 at 6300 to 6500 ft (1920 to 1981 m) by the assemblage of *Pterocaryapollenites*, *Ilexpollenites* sp., *Caryapollenites* spp., and "*Tiliaepollenites - Bombacacidites* complex" in the uppermost Kugmallit and lowermost Mackenzie Bay sequences (Dixon, 1990). A more marked Middle Miocene warm interval is evident in Ukalerk C-50 between at 5500 to 5700 ft (1676 to 1737 m) where *Pterocaryapollenites* sp., *Ulmipollenites*, *Ilexpollenites*, *Caryapollenites* spp., *Juglanspollenites*, *Fisheripollis* and *Saxonipollis* occur.

The late Early and Middle Miocene thermophilous assemblage is not evident in Mallik 5L-38, arguing that sediments corresponding to this time interval were either not deposited or were subsequently eroded. Lack of biostratigraphic control from this warm-climate Neogene assemblage is to be regretted. Also not represented is the pattern of progressive loss of now-exotic and thermophilous taxa that characterizes the late Middle and Late Miocene, and the pattern of a rise of herbaceous taxa, such as Poaceae and Cyperaceae that characterizes the continental late Miocene-Pliocene flora (White at al. 1997, 1999). As these bioevents are not represented, the probable age of the 340-700 m interval is Early Miocene.

Correlation using Tsuga

Tsuga has value for correlating this unit to sites in northern interior NWT, Yukon and Alaska. A tempting correlation of the occurrence of *Tsuga* and *Tsuga canadiensis*-type in Mallik 5L-38, 570 m to 900 m interval, to the late Miocene – early Pliocene resurgence of *Tsuga* spp., seen in Usibelli Group L2 and G zones (below), is not accepted here. The abundant presence of T-C-T pollen with *Tsuga* in Mallik , and its absence in L2 and G zones is evidence against this potential correlation. Moreover, *Ulmus* is a regular element in L2 and G zone assemblages and is not consistently present here (Leopold and Liu, 1994). *Baculatisporites* spp., co-existant with *Tsuga* spp. here, argues for an older age (below). Regional evidence of *Tsuga* spp. distribution is reviewed below.

In the Alaska Range, the Middle Miocene Suntrana Formation has *Tsuga* spp. at 5 to 10%, with up to four morphotypes in Zone S2. Above Zone S3A, *Tsuga* spp. distinctly decreases in abundance, with a resurgence of *Tsuga* cf. *canadensis* (up to 5%) in the upper Lignite Creek Formation, Zone G, of late Late Miocene age and Grubstake Formation, Zone G, of late Miocene–early Early Pliocene age (Leopold and Liu, 1994). White et al. (1999) recorded only minor occurrences of *Tsuga*, about 1%, at the Canyon Village section, Alaska, dated at 6.57±Ma (Kunk et al. 1994), and only about 0.3 % *Tsuga* in just two of five younger sections (White et al., 1999). Ager et al. (1994) recorded *Tsuga* sp. sparsely and at <1% in the Pliocene terrace gravels at Circle, Alaska. *Tsuga* sp. is not recorded in the Lower White Channel Gravel deposits at

Jackson Hill, Yukon, of probable early Pliocene age, nor in any of the younger preglacial and interglacial assemblages reported in Schweger et al. (2011). There is just one grain of *Tsuga* in 10 core samples of Pleio-Pleistocene age in Mallik 2L-38 (White, 2009).

In the Ukalerk C-50 well in the Beaufort Sea (Figure 12), *Tsugaepollenites* spp. is recorded by presence/absence (McNeil et al., 1982). It is consistently present in the late Oligocene to Middle Miocene upper Kugmallit and Mackenzie Bay sequences, and in the lower part of the Iperk Sequence, that is probably of Early Pliocene age (McNeil et al., 1982; Dixon et al., 1990). The Late Miocene Akpak Sequence is missing between the Mackenzie Bay and the Iperk Sequences in Ukalerk C-50 (Dixon, 1990; McNeil et al., 2001) due to the sub-Iperk Unconformity (McNeil et al., 2001), so the stratigraphic record is discontinuous. The top of the continuous record of *Tsugaepollenites* spp. is at 4700 ft (1432.6 m) in the Pliocene Iperk Sequence (McNeil and Birchard, 1989; Dixon et al., 1992) with two higher definite occurrences between 3700 and 3300 ft (1127.8 to 1005.8), these being at and above the occurrence of cf. *Polemonium* (3700 - 3600 ft, 1127.8 - 1097.3 m) (McNeil et al., 1982). *Polemonium* is a Plio-Pleistocene indicator (White et al., 1999). It seems unlikely that these Iperk Sequence occurrences of *Tsuga* are due to recycling, considering the lack of other taxa that would argue for a recycled assemblage.

To summarize the evidence presented above, in the Miocene there is variable, but consistently present percentage record of *Tsuga* spp. in the Alaska Range Usibelli Group and in the Beaufort Sea Ukalerk C-50 well, with a significant decline in *Tsuga* taking place in the latest Miocene or Pliocene. *Tsuga* was relatively rare in the Pliocene, but may occur in the record and should probably not be dismissed as recycled.

Local environmental conditions and short term climate variations are likely important determinants of *Tsuga* distribution, but are not well known. It is possible that the more maritime environment of the pollen catchment of the Ukalerk C-50 well was more amenable to *Tsuga* than the interior sites reported by White et al. (1999) and Leopold and Liu (1994). The warmth of the Early Pliocene (Ravelo et al., 2004) may have supported *Tsuga* occurrence, and latitude may have influenced the species of *Tsuga* occurring.

In spite of the Late Miocene and Pliocene occurrences cited above, McIntyre (1996) gives a mid-Miocene LAD for *Tsuga.* This conclusion derives from Adgo F-28, where *Tsugapollenites viridifluminipites* and *T. igniculus* have a LAD in the upper-Mackenzie Bay Sequence at 1900 ft. (579.1 m) (Norris, 1997), and from Nuktak C-22, where *Tsuga* spp. have a LAD at 2100 ft (640.3 m), in the upper Mackenzie Bay Formation (Norris, 1986). By its position in the Sequence (Dixon et al., 1992), one might infer the *Tsuga* LAD to be in the latter part of the Middle Miocene. In Nuktak C-22 and Adgo F-22, the Akpak sequence is missing between the Mackenzie Bay and the Iperk sequences (Norris, 1986, 1997; Dixon 1990), so potential late Miocene record of *Tsuga* spp. is absent. Hence, the mid-Miocene LAD picked for *Tsuga* by McIntyre (1996) is probably explained both by the decline in *Tsuga* spp. in late Middle and Late Miocene (Leopold and Liu, 1994), so that it is less likely to appear in the palynostratigraphic record, and by the absence of Late Miocene Akpak Sequence strata in which its resurgence might have been recorded.

Consideration of *Tsuga* argues for a correlation for the Mallik 5L-38 LAD of *Tsuga* spp., at 450 m, or the LAD of *Tsuga canadensis*-type, at 570 m. From the evidence in Nuktak C-22 or Adgo F-28, a minimum mid-Miocene age would be argued. In the absence of better age control, this could be penecontemporaneous with the Usibelli Group S3B - L1 zone *Tsuga* decline, estimated to be near 13 Ma (Leopold and Liu, 1994). However, the underlying Usibelli Group, Suntrana Fm. (S-2 and S3A,B) assemblages host a thermophile-rich late Early to Middle Miocene palynomorph assemblage, also documented by in the 15.2 Ma Upper Ramparts site (White and Ager, 1994). This thermophile-rich assemblage is not in evidence in Mallik 5L-38 below the *Tsuga* tops. Hence, while a mid-Miocene age for the *Tsuga* top derived from local wells is possible, an Early Miocene age, preceeding the thermophilus floral event, is preferred in this report for the 340 to 700 m strata. Unfortunately, the palynology of the Early Miocene in the Beaufort-Mackenzie Basin is poorly known**.**

In Mallik 5L-38, *Baculatisporites* spp. have a LAD at 610 m, probably equivalent to the occurrences of *B. crassiprimarius* and *B. quintus* in the mid- to lower Mackenzie Bay Formation between 2300 to 3199 ft (701 to 975.1 m) in Nuktak C-22 (Norris, 1986), and between 1900 to 2100 ft (579.1 to 640.1 m) in Adgo F-28 also the mid- Mackenzie Bay Formation (Norris, 1997; McNeil, in White, 2009). This also supports a minimum mid-Miocene age.

Unconformities

There are three potential events and/or unconformities within this 340 - 700 m interval: near the top of the interval at 340 m, where deposition of eroded material notably accelerates; at 445 m, where rocks uphole become less consolidated and more susceptible to erosion; and also near 550 m, where pollen concentration decreases downhole (Figure 12). If the Early Miocene age interpretation for this interval is correct, it implies a significant unconformity near 340 m with Early Miocene overlain by Plio-Pleistocene sediment, and with the Middle and Late Miocene and ?Early Pliocene missing. The changes at 445 and 550 m may represent the beginning of events that are not represented by unconformities.

The absence of Middle and Late Miocene sediment in the Mallik 5L-38 record is consistent with the sub-Iperk erosional unconformity that removed much of the late Miocene Akpak Sequence in many areas of the basin, and cut into the Mackenzie Bay Sequence (McNeil et al., 2001). The Iperk Sequence marks a sea level highstand and a progradation event into the basin, but Middle to Late Miocene sediment, deposited prior to Plio-Pleistocene glaciation, was probably removed by the erosion that developed the sub-Iperk unconformity or by subsequent glaciations.

Lane and Dietrich (1995) argued for a late Miocene tectonic pulse, but if the Early Miocene age interpretation of the 340 to 700 m interval is correct, the gradual rise of Recycled Palynomorphs within this interval argues that deformation increased in the Early Miocene. Other palynostratigraphic events record acceleration of the erosional process; i.e., the beginning of a rising trend in Sum Unknowns and Undeterminables at 550 m, and increasing fine comminution of organic matter at 445 m such that the +180 μm fraction is not separable. The low concentration of palynomorphs in the sediment is consistent with an erosive regional environment and high sedimentation rates in depositional areas.

As discussed by Norris (1997) for Adgo F-28, no dinoflagellates have been identified in the *Tsugaepollenites* interval in the Adgo F-28 or the Nuktak C-22 wells, even though foraminifera and dinoflagellates are present in a deeper water facies in Ukalerk C-50. As Mallik L-38 is inshore of those wells, the lack of dinoflagellates is consistent with the regional pattern for the Mackenzie Bay Sequence.

Gas zonation

Lorenson et al. (2005) divided the gas composition from Malik 5L-38 into gas zone 1 (0 to 350 m) that has microbial gas, and gas zone 2 (470 to 680 m) that has gas from a mixed thermogenic and microbial source of methane although thermogenic gas is relatively abundant. The transition between gas zones 1 and 2 occurs in the interval between 350 and 480 m. Thus, the gas zonation shows a similarity to the pollen zonation that has a disconformity identified at 445 m and a division at 700 m.

Interval 700 - 900 m

This interval has a relatively low percentage of taxa classified as Recycled and as Unknowns and Undeterminables. Also, counts are higher than in overlying strata, resulting in a greater probability of finding taxa (figs. 8, 9).

Ericales' interval of most regular occurrence is from 700 to 850 m; below and above this interval they are more sporadic, although sometimes more abundant. *Baculatisporites quintus* and *Baculatisporites primarius crassiprimarius* occur regularly between 710 m and 850 m and were not found in the samples below 850 m in Mallik 5L-38. *Tsuga canadensis*-type, with *Tsuga* sp., occur more regularly than elsewhere in the well between 730 and 830 m. Similar to *Baculatisporites*, they are rare below 830 m. These distributions suggest that there is another stratigraphic subdivision low in this interval, and a subdivision has been indicated at 850 m. There is a sampling gap between 875 and 890 m. This may point to stratigraphic complications not defined or understood.

The occurrence patterns of *Baculatisporites* spp., *Tsuga* spp. and Ericales are not identical in the Nuktak C-22 (Norris, 1986) and the Adgo F-28 wells (Norris 1997, and McNeil in White, 2009), complicating interpretation (Figure 12). Nonetheless, there are patterns of regular and intermittent occurrence in those wells that suggest arguments for correlation with the Mallik 5L-38, 700 to 850 m interval. In Nuktak C-22, *Baculatisporites crassiprimarius* ranges from the basal Richards into the mid-Mackenzie Bay Formation, but is common in the Arnak Member and the middle Richards Formation, and *B. quintus* occurs sporadically in the Arnak Member and the lowermost Mackenzie Bay Formation. In Adgo F-28*, Baculatisporites crassiprimarius* occurs in the mid- to lower Mackenie Bay and in the Taglu Formation, and *B. quintus* is sporadic in the mid- and lower Mackenzie Bay Formation. *Tsugaepollenites viridifluminipites,* in Nuktak C-22, occurs up to the mid-Mackenzie Bay Formation but is most common in the lower Mackenzie Bay and the upper Arnak Member, but also occurs commonly below. *Tsugaepollenites igniculus* is a sporadic Mackenzie Bay taxon. The Ericipites zone, Norris (1986) notes, is nearly co-extensive with the Nuktak C-22 Arnak Member, but occurrences of *Ericipites compactipollinatus* extends into the Mackenzie Bay Formation. Hence, these taxa between 700 and 850 m in 5L-38 suggest a correlation to the Arnak Member or general Kugmallit Formation or to the lower Mackenzie Bay Formation in Nuktak C-22 and Adgo F-28. The Ericipites Zone in Nuktak C-22 is probably of Late Oligocene age and the *Tsugaepollenites* zone of the Mackenzie Bay Formation may be latest Oligocene or more probably Miocene (Norris, 1986). These age interpretations are confirmed in more recent literature (McNeil, 1997; Norris, 1997).

In Mallik 5L-38, *Tsuga* occurs more regularly above 830 m and has a very limited representation below to 900 m. This suggests a possible correlation from 830 m to the base of the *Tsugaepollenites* range at 7100 ft (2164 m) in Ukalerk (McNeil et al., 1982) , which is below the LAD of the Oligocene marker *Turrilina alsatica* at 6700 ft (2042 m; McNeil and Birchard, 1989). The Oligocene is not subdivided in that well, but there is an interval from 7100 ft (2164 m) to 7400 ft (2255.5 m) , without *Tsugaepollenites.* The base of *Tsuga*'s regular occurrence in this interval would tend to support a correlation to the later Oligocene for the Mallik 5L-38, 700 to 830 m interval.

A climatic warm event is an aspect of the Late Oligocene and may figure in the interpretation of the Mallik 5L-38, 700 to 850 m interval. High resolution of Oligocene paleoclimatic cycles is provided by marine isotopic studies. The Oligocene is bracketed by transient glacial events, the earliest Oligocene Oi-1 event, ca. 33.6 Ma, and the earliest Miocene Mi-1 event, ca 23.2 Ma. Oligocene climate cycles responded to astronomical forcing, probably mediated by its effect on biosphere productivity (Pälike et al., 2006). The Oligocene warm interval occurred after ca. 26 Ma (Zachos et al., 2001), with peak warmth ca. 23-24 Ma within the late Oligocene, Phase IV isotopic interval (Pälike et al., 2006). Evidence from the southern North Sea basin likewise indicates that the Late Oligocene, Chattian Age, includes a climatic interval distinctly warmer than the Early Oligocene Rupelian Age. Tropical to subtropical sediments were deposited during a Chattian marine transgressive event (De Man and Van Simaeys, 2004; Van Simaeys, 2004). The Arnak Member in the Beaufort-Mackenzie Basin (Norris, 1986) is of Late Oligocene (Chattian) age and Norris (1982) has indicated that the Arnak Member was deposited during a climatic interval warmer than the underlying Ivik Member, consistent with the global climatic pattern. In the Mallik 5L-38, 700 to 850 m interval, the presence of *Tsuga* spp., *Baculatisporites* spp., *Pterocarya*, *Ulmus*-type and rare occurrences of *Carya* and ?*Magnolia*, suggest a temperate climate. The assemblage is similar, but not identical to the Ukalerk C-50 interval, 6300 to 6500 ft (1920 to 1981 m), which has an assemblage including *Pterocaryapollenites*, *Caryapollenites* spp., *Ilexpollenties* and the"*Tiliaepollenites - Bombacacidites* complex" (McNeil et al ., 1982). Nonetheless, the evidence for Late Oligocene, Chattian, climatic warmth is much less definite at this high latitude than it is in the North Sea. This may be a result of the nature of the climatic event, and/or of its visibility using well cuttings.

The interval in Mallik 5L-38 from 830 m to 900 m with minimal *Tsuga* spp. and from 850 to 900 m without *Baculatisporites*, may represent an interval in the Early Oligocene falling within the cooler climate, Ivik Member of the Kugmallit Formation (Norris, 1882, 1986). There is a decline in the Count Sum of Terrestrial Palynomorphs and in the Palynomorph Concentration below 850 m, but other taxa range through this interval. Hence, this might represent some interval of time within the Rupelian Age .

As a tangential consideration, a paleoclimatic perspective may explain the occurrence of some taxa whose stratigraphic patterns are episodic -for example, *Triatriopollenites granilabratus* (Stanley 1965) Norton in Norton and Hall 1969. *T. granilabratus* occurs in Mallik 5L-38 at 830 and 840 m. It is illustrated from the Caribou Hills by Parsons (2000, Pl. 9, figs. 31-33, 39) and is found in CHE 1 to CHE4b, of Late Paleocene and Early to Middle Eocene age. Morphologically, *T. granilabratus* compares favourably with *Ostryoipollenites* sp. cf. *O. rhenanus* (Thompson) Potonié ex Potonié 1960 in Nuktak C-22. There, *Ostryoipollenites* sp. cf. *O. rhenanus* is found stratigraphically in the lowermost Mackenzie Bay and Arnak equivalent interval, 3000 to 4700 ft (914.4 to 1432.6 m) (Norris, 1986, Pl. 10, Figure 35-37), although in Nuktak C-22 it is not found in the Richards or Taglu Formations. The presence of this taxon in Mallik 5L-38 and Nuktal C-22, above Parsons' older Caribou Hills occurrences, could be taken as evidence of recycling, but it might also indicate that this taxon is a thermophile and indicative of a warm interval, such as characterizes the late Oligocene (De Man and Van Semaeys, 2004).

Gas Zonation

A transition between gas zones 2 and 3 occurs between 680 and 785 m, between which falls the 700 m biostratigraphic division proposed herein. Gas zone 3, from 785 to 1165 m (TD) may have gas contributions from lignite seams (Lorenson et al., 2005), which are discussed below.

Disconformity near 930 m

The Oligocene Antarctic glaciation caused sea level lowering of at least ~ 55 m (Miller et al., 2005; Śliwińska and Heilmann-Clausen, 2011). A sharp or erosional sedimentological boundary was assigned at 926.5 m in Mallik 2L-38 (Jenner et al., 1999) and Medioli et al. (2005) identified a "significant" boundary at 932.6 m in Mallik 5L-38 (Figure 12). White (1999) suggested that this approximated the Eocene-Oligocene boundary. The Oi-1 glaciation followed the Eocene-Oligocene boundary by about 800 kyr (Deconto and Pollard, 2003), but it likely formed an erosional disconformity identified in the Mallik wells, with an undetermined loss of sedimentary record.

Interpretation of Paleoclimatic Proxy Ratios

The analysis of 5L-38 complements that of 2L-38 and fills in the biostratigraphic information for the strata above 670 m. By research design, the study interval in the 5L-38 well overlaps the 900 m to 660 m interval in the 2L-38 well so that the results for this overlapping interval can then be compared. The pollen concentration values are in good agreement in this overlapping interval (above), but the pollen ratios show differences that require consideration. The 5L-38 ratios were calculated using the same taxa reported in 2L-38, although the thermophilous angiosperm assemblage in 5L-38 is impoverished compared to 2L-38.

Figure 10 shows the pollen ratios Mallik 2L-38 (White, 2009) and 5L-38 that serve as experimental proxies for paleotemperature. All ratio series have been minimally smoothed with a 3-point moving average to emphasize trends over short-term variation and noise. A problem in interpreting these ratios is that no other such ratio calculations have been done for the Beaufort-Mackenzie Basin, except those reported here for the Mallik wells; indeed, there has been no published quantitative palynostratigraphy in the Beaufort-Mackenzie since Staplin et al. (1976). First, the ratio curves for 2L-38 need to be summarized.

In the Mallik 2L-38 study, paleoclimatic interpretation was derived from nearly in-phase patterns of independent ratios of taxa. Simultaneous peaks in the *Pinus*/*Picea* and Temperate Angiosperms/Total Angiosperms in the lower cored interval near 950 m gave confidence that the ratios reflected real vegetation events, even though those simultaneous peaks were probably driven by short-term edaphic conditions affecting *Pinus* and *Ulmus*. Two ratios, T-C-T/Total Pinaceae and Temperate Angiosperms minus *Ulmus*/Total Angiosperms, are more stable proxies for climatic temperature. From 1150 to ~ 890 m these two ratios follow a general declining trend with joint peaks around 1110 m, and another muted offset peak around 1050 to 1010 m. Their similar patterns of long term decline to low values at about 890 m is suggestive of a long-term climatic cooling event that which is thought to culminate in the early Oligocene cold event. However, in the 890 m to 670 m interval of Mallik 2L-38 the ratios are no longer in phase. Moreover, a more detailed comparison of the patterns in the overlapping section of the 2L-38 and 5L-38 wells, and in the different ratios within the 5L-38 well, reveals dissimilarities. Those discordant patterns may be due to vegetation re-organization, recycled taxa, statistical noise associated with low counts, or processing. The reason is not obvious but cautious interpretation is advised.

In Mallik 5L-38 a similar pattern of ratios is found in Temperate angiosperms / Total angiosperms and Temperate angiosperms minus *Ulmus* / Total angiosperms. In the 2L-38 well *Ulmus*-type pollen is a significant fraction of the temperate angiosperm pollen. In 5L-38, *Ulmus* -type is a relatively small and sporadic component of the angiosperms (Figure 9) and the thermophilous angiosperm curves with, and without *Ulmus*-type grains are very similar. These curves can be referred to as the "angiosperm ratios" due to their similarity. Both Angiosperm curves show small peaks between 850 and 700 m in the interval that is interpreted as probably representing a warm Chattian Age (above). What is unexpected, considering previous discussions, is the gap in values between 800 and 760 m.

In Mallik 2L-38 (White, 2009), the ratios used for paleotemperature interpretation for the section below ~890 m were the T-C-T/Pinaceae and Thermophilous angiosperms minus *Ulmus*/ Total angiosperms. In 5L-38 there is a similar, but not perfectly in phase, bimodal pattern to these curves with peaks about 820-800 m and 730 m, and low values about at 770 and 650 m, with a subsequent rising trend. Angiosperm ratios of temperate taxa to all angiosperms is lower in 5L-38 than in 2L-38 in the overlapping 900 to 660 m section and the ratios are not in phase. However, what is similar between the two wells is the relatively low values in the 900 to 850 m interval with increase in overlying section to 800 m.

The upper limit of useful information in the angiosperm curves is 520 m as the pattern above reasonably reflects the onset of deposition of abundant eroded organic and inorganic sediment. The fact that the T-C-T/Pinaceae continues to show strong patterns even within this interval of regional erosion likely reflects the relative sources of older (T-C-T dominated) and younger (Pinaceae dominated) recycled material.

The 5L-38 *Pinus/Picea* record does have similar pattern with the angiosperm curves in the interval of between 900 and 700 m, a pattern formed chiefly by the low values about 760 - 780 m, but the patterns are very dissimilar between 700 and 600 m. Moreover, these ratios are not similar to those in Mallik 2L-38 between 900 and 660 m.

In summary, Figure 10 shows that the ratio patterns in the overlapping section of the two wells are problematic. The absolute values of the ratios are different – generally higher values in 2L-38 than 5L-38, excepting the *Pinus*/*Picea* ratio. There are higher values of Temperate angiosperms/Total angiosperms for 2L-28 compared with 5L-38. In spite of similarities noted above, for any ratio, the cycles of high and low values are generally not in phase between wells, and patterns of the ratios do not correlate within each of the two wells. One would expect the 2L- and 5L-38 wells, within a few hundred meters of one another, to have comparable patterns. Nonetheless, in the Mallik 5L-38 ratios (Figure 10), a common feature of the 900 to 800 m interval is a rising trend implying climatic warming, a pattern which generally matches that found in the 2L-38 well.

Some difference in patterns may be explained in part by lithological offsets. Within the gas hydrate bearing zone, gas hydrate saturation is strongly controlled by lithology, occurring in well- sorted sand and pebble beds, rather than in fine-grained sediment. A relatively straightforward correlation by depth between the 2L- and 5L-38 wells is supported by a fence diagram of gas hydrate saturation (Dallimore and Collett, 2005, Figure 6) and by magnetotelluric log (Craven, 2007) assessment of hydrate presence. However, in finer detail there are about 10 m offsets in vertical distribution of fine- and coarse-grained deposits, probably due to differences in fluvial deposition and erosion. Such offsets may contribute to, but are not sufficient to explain the differences in ratios seen in Figure 10.

Modifications of processing in Mallik 5L-38 by use of acetolysis (above) may have affected the results here, but changes in character and concentration of organic matter demanded an adaptation of processing, which also yielded insights regarding recycling. Further experience may allow palynologists to settle on a processing standard for these difficult strata.

Statistical noise in the ratios when count sums are low, as in these studies, is a significant factor in comparing palynomorph ratios. Improvement in counts and saturation of the rarefaction curve would surely lead to improved results, but this may be impossible to achieve in zones of low concentration where very large samples of cuttings are not available. The zone of overlap of analyses is one of very low palynomorph concentration in both wells.

The drop in pollen concentration values above 886 m in Mallik 2L-38 (White, 2009), corroborated by this study of 5L-38 (Figure 8), and the problem of deriving a palynological signal due to recycled palynomorphs in both wells above 886 m may set a limit to paleoclimatic inference. This pattern may be an indicator of change in regional sedimentation and/or paleoclimate. That is, in itself, a valuable piece of evidence that suggests a significant geological event ca. 886 m. The problem of the comparing ratios within wells and between wells above 886 m is in contrast to the more coherent pattern of ratios from Mallik 2L-38 below 886 m.

Paleoclimatology by palynology would be most successful when applied over long stratigraphic intervals with relatively good recovery of palynomorphs. It will take some time to develop such analyses in the Beaufort-Mackenzie Basin, but recognition and tracking of the role of climate in driving biostratigraphic change would seem to be a fruitful research strategy for work in the Basin, considering that climate was a driving force for Cenozoic floristic and vegetation change.

PALYNOLOGY OF COALS FROM CORE, 933 M TO 1151 M

The Mallik 5L-38 well was cored from 885 to 1151 m, yielding 192.6 m of core (Dallimore et al., 2005). Sedimentology and photographs of the cores are found in Medioli et al. (2005). Fifteen coal samples were collected from core in the 141 m interval between 933.65 and 1081.90 m. By simple depth correlation to Mallik 2L-38, 100 m to the northeast (above), these samples fall within the strata interpreted to be of Late Eocene age (White, 2009).

The coal samples are from stratigraphically clustered coals and the clusters are separated by up to 64 m. Consequently, the samples will be discussed by 4 stratigraphic intervals, 933.65-940.95 m, 1005.18-1005.56 m, 1043.16-1053.68 m, and 1081.90 m, each having a single sample or closely-spaced multiple samples. Samples are from 1 to 3 cm thick beds and are plotted by their bottom depth (Figure 11), used to identify them in the discussion below. Discussion for each interval includes the description of the assemblage with appropriate taxonomic notes, plus interpretations of the age, paleoclimate and paleoenvironment, and comparison of the results with other organic and geochemical analyses. The 15 samples had a range of 65 to 326 palynomorphs counted per sample, with an average of 241.13 palynomorphs per sample.

Recycling Considerations

These are samples from coal beds, not from detrital coal. Photographs of these coals are found in Medioli et al. (2005) for samples from 933.65 m through to 1005.56 m, and in the compact disk accompanying G.S.C. Bulletin 585 (Dallimore and Collett, eds., 2005) for the 1043 m, 1053 m and 1081 m interval samples. There is little chance that palynomorphs recovered from coal cores are recycled. Coals develop from organic-rich deposits of former wetlands. Such environments minimize external clastic input, which is the source of recycled palynomorphs.

Vegetation representation

Sediments of wetlands - marshes, bogs or forest swamps - provide excellent environments for plant growth and for pollen and spore preservation. If plants are growing right in these wetland environments, those plants are highly represented in the pollen and spore assemblage that wetlands preserve. Pollen rain from the surrounding, regional upland vegetation may be a smaller component of the wetland pollen record. Indeed, assemblages from coals commonly have low diversities (Frederiksen, 1985). The unusual, low-diversity palynological assemblages discussed below, dominated by Ericales or *Laevigatosporites*, argues that the wetlands are not representative of the diversity of the upland flora, which would more likely be preserved in lacustrine sediment.

Wetlands also have growing conditions that set their vegetation apart from the regional upland vegetation. Stresses on wetland plants may include anaerobic growing conditions and acidity, but other conditions that stress upland plants are moderated, including seasonal temperature and moisture extremes. Hence, wetland species may span several upland vegetation zones. Nonetheless, changes in the edaphic conditions, such as water table or nutrient conditions, can significantly affect the dominant vegetation of wetlands.

Paleoclimatology

Palynomorphs from coals can be used to derive paleoclimatic temperature estimates. Paleotemperatures are estimated from the climatic tolerances of the living North American relatives of the fossil genera identified here, using climatic data from the detailed study of Thompson et al. (1999a,b; 2001). Many of these taxa also have relatives in Asia, but for these no climatic tolerance data comparable to those of Thompson et al. have been published. The interest here centres on the minimum warmth indicated by the thermophilous species.

Fossil genera have a varying number of modern relatives in the United States, ranging from *Quercus*, with 57 species, to *Liquidambar* with only one species as a modern relative. To approximate the minimum temperature conditions that these fossil species or genera could tolerate, the estimates below are derived from both the most broadly and the most northerly distributed modern relatives. Species with localized and/or more southern distributions have been omitted. Species are limited in temperature both by their tolerance for extreme cold in the winter, and by their need for heat during the growing season. The January minimum mean monthly temperature range of modern species is an estimate of their cold tolerance, below which they are unlikely to survive. The July minimum mean monthly temperature range is an estimate of the minimum temperature they need in order to grow. The tolerances of modern relatives do not converge on single values for paleotemperature estimates, but are best expressed as a range of January and July minimum mean monthly temperatures. Moisture estimates are not considered here, but Thompson et al. (1999a,b; 2001) can be consulted for the information.

933.65 - 940.95 m

Assemblage and Age

This assemblage comprises five samples in two closely spaced groups: 933.65, 933.93 and 934.21 m, underlain by 940.53 and 940.95 m samples. *Alnus*, Ericales, *Laevigatosporites, Triporopollenties* and *Ulmus*-type are common to abundant with some T-C-T and little Pinaceae pollen.

A Late Eocene age is suggested by critical palynomorphs in this sample. *Jussiaea* sp. (*Ludwigia*) and *Boisduvalia clavatites* (both at 940.95 m) were described from the Australian Creek Formation of central British Columbia (Piel, 1971), now considered to be of Late Eocene age (Long and Sweet, 1994). *Lonicerapollis gallwitzii* occurs in the sample, and in the Mackenzie Bay and upper Kugmallit formations in Adgo F-28 (Norris 1997, McNeil, in White, 2009) and A.R. Sweet notes that it ranges down into the Eocene in northern Canada (pers. comm., 18 Feb 2005). It also occurs in the Middle Eocene in southern California (Frederiksen et al., 1983),). *Mancicorpus* sp. of Ridgway et al., 1995 (940.95 m), is found in the Amphitheatre Formation, Yukon, in Biozone 1 at Steele Creek and 1b at Cement Creek, in strata of Late Eocene to possibly Early Oligocene age (Ridgway et al., 1995).

The occurrence here of the new triprojectate pollen, *Striatocorpus sweetii* White 2009 (934. 21 m) extends its stratigraphic range upwards from the observed 990.0 m to 1140.0 m in the Mallik 2L-38 well, although it is still in the Late Eocene. This occurrence demonstrates that it at least partly overlaps the range of *Manciporpus* sp. of Ridgway et al. 1995 (940.95 m) but this single occurrence of *Mancicorpus* in the Mallik 5L-38 well is insufficient to make firm conclusions about the relative ranges of these two taxa.

Mancicorpus sp. of Ridgway et al., 1995 (Figure 13, I) differs in shape from *Striatocorpus sweetii*, described from the Mallik 2L-38 well (White, 2009). *Mancicorpus* sp. has a larger equatorial diameter versus polar diameter and downward-raked, relatively pointed projections. *S. sweetii* lacks *Mancicorpus* sp.'s strong concave flexure between the polar dome and the equatorial projections. *Mancicorpus* sp. of Ridgway et al., 1995 and *S. sweetii* White 2009 are clearly closely related species, but the observation of more specimens to elucidate population variability is required to clarify their relationship. **[**Morphological note: At 940.95 m (C-400953), one specimen of *Mancicorpus* sp. of Ridgway et al., 1995 (a-13.8/11.3) is 20/30 μm in polar/equatorial axes (respectively), another (a-13.9/11.0) is 20/32 μm, and a faint infra-reticulum is visible on this specimen. The specimen of *S. sweetii* at 934.21 m is 18/28 µm and is shaped like the holotype (White, 2009, Plate 5, Figure 22). An occurrence of *S. sweetii* at 680.0 m is in the +180 μm fraction (C-432733, "683.66 m", b-35.9/8.1), is 24/28 μm and is more rhombic-shaped or isopolar with a faint infra-reticulum. This shape matches a specimen (White, 2009; Plate 5, Figure 23) that was included in *S. sweetii* because of its stratigraphic proximity to the holotype, so it was included as perhaps representing the range of variation of the species (White, 2009). Perhaps this latter morphology should be separated from *S. sweetii***]**.

Zelkova-type is reserved for 3-pored Ulmaceae grains, as Leopold and Liu (1994) indicate that *Zelkova* is 3- and 4-pored and *Ulmus* and *Planera* would generally be 4- to 6-pored (Lieux, 1980b)]. *Nyssa* is present and *Carya* and Poaceae pollen are questionably present.

There are specimens recorded as *Triporopollenite*s which would compare well with *Momipites wyomingensis* as illustrated by Norris, 1997 (Plate 7, figs. 4, 8). Norris (1997, p. 12) questions the standard interpretation that *Momipite*s and *Caryapollenites* in the Adgo F-28 *Integricorpus* zone are recycled from the Paleocene. The occurrence of these specimens in Mallik 5L-38 coals supports Norris' interpretation.

In Mallik 2L-38 at 946.2 m, near the stratigraphic interval described here, Kurita and Uchida (1999) described a small dinoflagellate assemblage of Paleocene to Eocene age. They dismissed this assemblage as recycled, although the age is compatible with that derived from pollen and spores herein and in Mallik 2L-38 (White, 2009).

Paleoclimate

The modern North American distribution of *Nyssa* pollen suggests a minimum, limiting mean monthly temperature range for January and July of -12° and 15° C, respectively (Table 8). *Planera aquatica* could produce pollen similar to *Ulmus-type*, it was not used for the paleotemperature estimate because *Planera* has a very limited modern distribution in warm, southern USA, compared with the broader and more northerly distribution of *Ulmus* that ranges into southern Canada. *Ulmus*-type generally supports the paleoclimatic interpretation based on *Nyssa*, but can tolerate limiting minimum mean monthly temperatures for January and July of -23° and 13° C, respectively. *Carya* would require warmer winters and summers of -17° and 17° C, respectively. The range of minimum mean monthly temperatures for January are -17° to -23° C and for July and 13° to 17° C (Table 8).

Paleoenvironment

The abundance of *Alnus*, Ericales and *Laevigatosporites* together with some Pinaceae and T-C-T pollen suggests limited local arboreal vegetation.

These samples fall within Medioli et al.'s (2005) Unit 2 of fluviodeltaic deposits. A boundary at 932.64 m, just above these palynological assemblages, is similar to Jenner et al.'s (1999) 926.5 m boundary in Mallik 2L-38. In that this is a zone of active subsidence on a listric fault (Brent et al., 2005; White, 2009) the timing and rate of subsidence may be a factor. However, it is suggested above that this boundary may be an unconformity associated with sea level downdraw due to the Oi-1 Antarctic glaciation.

Haberer et al. (2005) identified organic matter in the Mallik 5L-38, 891-1145 m interval, as being of dominant terrestrial origin from a lower delta-plain or lacustrine-influenced environment with a community of gymnosperms, angiosperms and mosses (*Sphagnum* sp.), although bryophyte spores in general and *Sphagnum* in particular are rare to absent in the palynological coal samples. Based on geochemical analysis of the zone from 930 to 1000 m in

5L-38, Chen et al. (2005) have suggested a coastal marsh with shallow-marine sediments, and with varying marine influence during the deposition. Organic matter was derived from land plants and marine algae. In the adjacent Mallik 2L-38 well, Jenner et al. (1999) describe the sedimentology of the 926.5 to 952.2 m interval as being clayey silt, massive to weakly laminated, poorly to moderately bioturbated, with interbedded low-rank coal. The results from sedimentology, organic petrography, geochemical analysis, and paleontology are complementary and entirely consistent with a marginal marine, lower delta plain environment with organic-rich deposits. During an episode of maximum marine influence, it would be consistent with Kurita and Uchida's (1999) small dinoflagellate assemblage.

1005.18 - 1005.56 m

Assemblage and Age

These five samples are rich in pollen and spores. Even more than the coal samples 64 m above, this interval is dominated by Ericales, and could provide material for a study in Ericale morphological diversity. *Nyssa* sp. occurs more abundantly than in the other coals and fungi are well represented. *Laevigatosporites* is sparse compared to other samples. The pollen assemblage suggests a large swamp dominated by heaths, alder and tupelo. As above, there are no identifiable *Inapertisporites dubius* (most likely T-C-T pollen) and minimal Pinaceae pollen.

?*Brefeldiellites* sp. (1005.56) m is an ostiolate sheet of poorly arranged fungal cells. Two species have been described from the Early Cretaceous and the Early Eocene. The Early Eocene species, *B. frictiflabellis* Dilcher 1965, was epiphytic on a host leaf of *Chrysobalanus* (Kalgutkar and Jansonius, 2000), a plant now growing in Florida (USDA, NRCS; 2006).

?*Viburnum* sp. cf. *V. cassinoides* of McIntyre 1991 (1005.18 m) was previously found in the Axel Heiberg fossil forest, where it is of Middle or possibly Late Eocene age (McIntyre, 1991). *Desmidiospora willoughbyi* (1005.18 and 1005.41 m) has been found in strata designated as Eocene, and Late Eocene (Kalgutkar and Jansonius, 2000).

Fungal hypha type D of Norris 1986 (Plate 4, Figure 11-14) occurs in Mallik 5L-38 at 1005.18, 1005.38, 1005.41 and 1005.56 m. Fungal hyphae type D of Norris 1986 occurs sporadically in the Nuktak C-22 well in the Richards Formation and Ivik Member of the Kugmallit Formation, and has a LAD in the overlying Arnak Member (Norris, 1986).

Lonicerapollis gallwitzii Krutzsch 1962 occurs in sample 1005.31 m, and its range is discussed above.

Paleoclimate

This groups of samples contains many taxa suggesting warm climatic conditions: *Carya* (1005.56 m); *Ilex*-type pollen (all samples but 1005.56 m), representing *Ilex* or the very small genus *Nemopanthus* (White and Ager, 1994); *Juglans* (1005.31 m); *Liquidambar* (1005.18 m);

Nyssa (in all samples and in unusually abundance in 1005.38 m); *Quercus* (1005.18, 1005.31 and 1005.38, m) and *Ulmus*-type (all samples). These taxa suggest a broad range of minimum limiting mean monthly temperatures for January of -4° to -23° C, and for July of 13° to 17 ° C (Table 8). There are many multicellular fungal sheets of ?epiphylous fungi, including ?*Brefeldiellites* sp., suggesting a humid climate.

Paleoenvironment

The abundance of Ericale pollen in this interval suggests an acidic wetland, but the absence of commonly associated bryophyte spores such as *Sphagnum* suggest that the pH was likely above 4.5 (Zoltai, 2006), suggesting flow of surface or ground water through the wetlands. The dominance of Ericales, with little upland coniferous pollen from the T-C-T or Pinaceae, has three conceivable explanations; a broad extend of wetland that attenuated regional pollen rain input, the actual low occurrence of conifers in the regional vegetation, or overwhelming dominance of Ericales in the local vegetation.

The commonness of fungi in the lower sample (esp. Fungi hyphae, *Inapertisporites* sp., *Monoporisporites* sp.) and of *Nyssa* (1005.38 m) suggests environmental development that may be a hydroseral succession from moist to inundated conditions, and may have to do with changing base levels controlled by climate, eustacy or tectonics. In North America *Nyssa* commonly inhabit moist soils and swamp-lands in the southeastern temperate forests (Everett, 1969), ranging north to southern-most Ontario. *Nyssa sylvatica* likes moist acidic soils but will grow on dryer, upland soils (Hosie, 1969). However, its tolerance to wetland is consistent with its occurrence in a coal.

The coal bed sampled here, and those described below, are in sedimentological Unit 4, consisting of, "... overbank and floodplain deposits grading into upper delta-plain deposits." (Medioli et al., 2005). Chen et al. (2005) describe the 1000 to 1070 m interval, encompassing this 1005.18 to 1005.56 m suite of samples and the 1043.16-1053.68 suite below, as a coastal coal swamp where all of the organic matter was derived from land plants, based on geochemical analysis.

1043.16 - 1053.68 m

Assemblage and Age

Compared to the samples 38 m above, these four samples have many fewer Ericales but more abundant Pinaceae and T-C-T and *Inapertisporites dubius. Inapertisporites dubius* is probably a T-C-T pollen, being comparable to pollen of the bald cypress, *Taxodium* (Lieux, 1980a, Pl. VII, Figure 6), although papillae were not seen. There is considerable plant and fungal tissue.

Pistillipollenites macgregorii (at 1043.32 m) has been considered an indicator of a Late Paleocene to Middle Eocene age (Rouse, 1977) but evidence from the Mallik 2L-38 well (at 1000 m) and from other occurrences discussed in White (2009), argues that it ranges into the

Late Eocene. Fungal hypha type D of Norris (at 1053.49 m), also is consistent with an Eocene age (above). *Jussiaea* (*Ludwigia*) sp. is of Late Eocene age (above).

The distinctive pollen, *Erdtmanipollis procumbentiformis* (1043.32 and 1053.69 m) is closely related to *Pachysandra* and *Sarcococca* of the small, predominantly Old World family, Buxaceae. One species of *Pachysandra* occurs in southeastern United States and one species of *Sarcococca* occurs in southeastern Mexico and Guatemala. Pollination ecology is such that it would rarely be found in the sedimentary record. (Gray and Sohma, 1964; Leopold and MacGinitie, 1972).

Psilastephanocolpites cf. *marginatus* of Norris 1997 (1043.32, 1053.68 m) occurs in one cuttings sample at 3800 ft in Adgo F-28 in the uppermost Taglu Formation, virtually at the contact with the Richards Formations (Norris, 1997). Its occurrence here argues that it ranges upwards into the Late Eocene.

Alder pollen grains with a polar annulus are designated by different names. Here *Alnus* sp. cf. *seiboldiana* is used following Simpson's (1960-61) interpretation that the species *Alnus scotica* Simpson 1961 (p. 448) is similar to the modern pollen of *A. seiboldiana* of Japan. Parsons (2000) uses *Alnipollenites scoticus* (Simpson) Pocknall and Nichols 1996 for similar pollen, that range from her zone CHE1 (Late Paleocene) through the lower part of CHE4c (?Late Eocene/Oligocene) but is most common in CHE4a and lower CHE4c. This *Alnus* type is within the range of *Alnipollenites verus* (A. Sweet, personal communication, 21 February 2007).

Paleoclimate

Pachysandra and *Sarcococca* (*Erdtmanipollis procumbentiformis*) are not included in Thompson et al. (1999a, b; 2001) but the distribution of *Pachysandra procumbens,* according to the Plants database (USDA, NRCS, 2007), is similar to *Liriodendron tulipifera* in Thompson et al. (1999b), for which they provide climatic tolerances. This suggests a minimum mean monthly temperature for January and July of -10 and 17° C, respectively, based only on this taxon.

Paleoenvironment

The assemblage is limited but the reduced abundance of Ericales and greater abundance of Pinaceae and T-C-T than in overlying samples suggests a more upland-dominated pollen assemblage**.**

1081.87 - 1081.90 m

Assemblage and Age

This one sample yielded an abundant assemblage overwhelmingly dominated by the fern spore, *Laevigatosporites* sp., along with Liliaceae pollen and Ericale pollen, but much less of that than in overlying assemblages. One specimen of *Magnolia* pollen occurs (see Lieux,1980a, Pl. X, figs.1-7).

?*Viburnum* sp. cf. *V. cassinoides* of McIntyre 1991 suggests an Late Eocene age (above). The ornament of the Mallik specimens is fainter than McIntyre's specimens.

Aquilapollenites sp. cf. *A. quadrilobus* has less well developed spines than the classic Cretaceous form, but falls in this category. *A. quadrilobus* ranges into the Paleocene, but A. Sweet has never seen a population of specimens that convinces him that it legitimately occurs in younger strata (A. Sweet, pers. comm, 16 March 2006). Nonetheless, its presence here in a coal argues that it is not recycled and that it ranges into the Late Eocene is certain environments.

In the adjacent Mallik 2L-38 well at 1100 m, McNeil (1999) identified one specimen of *Haplohragmoides carinatus*?, a foraminifer with a late Eocene to middle Miocene stratigraphic range, but McNeil considered the single specimen to be too limited evidence for definitive conclusions. Nonetheless, the late Eocene age is compatible with the age based on pollen and spores (herein, and White, 2009).

Paleoclimate

Magnolia pollen argues for a warm climate with minimum limiting mean monthly temperatures for January of -3 to -7° C and for July of 18° to 22°C. However, there are no other indictor taxa to support this interpretation.

Paleoenvironment

The abundance of ferns would seem to indicate a less paludal, acidic environment than indicated by the Ericale-rich samples above, although it was sufficiently inundated to accumulate organic matter. Based on geochemical analysis, Chen et al. (2005) describe the 1070 to 1150 m interval of this well as a lower to upper delta-plain, with the lower half (below this sample) strongly influenced by marine incursions.

Summary of palynology from coal cores

Age

Pollen and spores found in coal beds are much less likely to be recycled than those from clastic beds, and photographs of cores clearly demonstrate that the samples analysed are not from recycled, detrital coal. Biostatigraphic indicators such as *Boisduvalia clavatites, Jussiaea* (*Ludwigia*), *Mancicorpus* sp. of Ridgway et al. 1995, *Pistillipollenites macgregorii* and *Psilastephanocolpites* cf. *marginatus* of Norris 1997 argue for a Late Eocene age.

Paleoclimate

Taxa are present whose modern relatives have warm climatic requirements, typical of the southeastern United States. The summary "Range of temperature limits" of Table 8 are the lower range of the possible temperatures because they are derived from the more northerly distributed modern relatives. January minimum mean monthly paleotemperatures may have been as low as -23° C, but were likely much warmer. July minimum mean monthly temperatures are at least 13° C, but were probably warmer. These beds correlate to the interval in the adjacent Mallik 2L-38 well, for which a Late Eocene age was assigned (White, 2009).

In Alaska, Wolfe (1992) notes that the age separation between the latest Eocene Rex Creek and the probable Oligocene Angoonian megafloral assemblage is not well controlled, but the Climate Leaf Analysis Multivariate Program (CLAMP) gives a Mean Annual Temperature (MAT) estimate for the Rex Creek flora of ~15°C, whereas the small Angoonian assemblage yielded a MAT of ~4.5°C. By isotopic measurements of teeth and bone from mammal fossils, Zanazzi et al. (2007) have estimated an 8.2±3.1°C temperature drop in mid-continental North America across the Eocene-Oligocene transition. The paleoclimatic inference from the Mallik 5L-38 coals is clearly consistent with an Eocene climate. The direction of temporal change of estimated paleotemperature in the Mallik coals trends towards cooling, consistent with the direction of change indicated by pollen ratios (White, 2009), although the range of potential temperature estimates is broad.

Paleoecology

These coal samples reveal aspects of local wetland ecology of the Late Eocene. The pollen assemblages from coals are skewed towards representation of the local wetland floras, which are apparently mostly heath (Ericale) dominated, with ferns dominating the lowest sample. The upland floras of arboreal angiosperms, T-C-T and Pinaceae are much less well represented.

The general absence of strong T-C-T and Pinaceae representation in these samples needs explanation, as they are common elements of Eocene assemblages. The Pinaceae are generally intolerant of inundated substrates, in spite of exceptions such as *Pinus serotina* and *Picea mariana*. Although generally high pollen producers, the Pinaceae could be poorly represented if the paleoenvironment were an extensive wetland system that hosted local pollen producers.

The wetland ecology and pollen representation may be explicable if one considers the influence of pH. Samples 1043.16 - 1053.68 m have an abundant representation of the taxon *Inapertisporites dubius*, here argued to be T-C-T pollen. Within the Taxodiaceae, *Taxodium* would be consistent with the wetland environment, and *T. distichum* (bald cypress) is the most wide-ranging modern *Taxodium* in the United States. It is adapted to fine-textured substrates and wet environments, with a pH tolerance of 4.5 to 6.0 (USDA, NRCS, 2006). In contrast, samples from 933.65 to 1005.56 m are dominated by the Ericales. A wetland Ericaceae such as *Ledum groenlandicum* can tolerate a pH of 5.0 (USDA, NRCS, 2006). Hence, an abundance of Ericales may indicate wetland with a pH about 5.0, limiting competition from other species, but the absence of bryophyte spores, such as *Sphagnum,* in all samples likely indicates a pH above 4.5 (Zoltai, 2006). This would argue for flow of surface or groundwater through the sites, and is consistent with a floodplain environment.

The contrast between the *Laevigatosporites*-dominated assemblage in the lowest, 1081.90 m sample and the overlying Ericale-dominated assemblages suggests that distinct climatic change or a change in the regional edaphic environment was involved; the latter is a strong possibility. The position of the Mallik wells on a continental marginal fault block (Brent et al., 2005; White, 2009) makes it susceptible to tectonic adjustments of base level, which may have resulted in two different associations of wetland plants.

Relict Survival of Species in Wetlands

White (1999) erroneously interpreted the Mallik 2L-38 interval, 995 to 1150 m, as Early to Middle Eocene, based on taxa that are associated with the Aklak and Taglu Sequences. In this study, two indicator taxa, *Pistillipollenites macgregorii* and *Psilastephanocolpites* cf. *marginatus*, associated with Early to Middle Eocene ages, are found in Late Eocene strata where recycling can be virtually ruled out. An explanation may be that the plants survived as relicts in the wetland environments. This explanation would appear to apply also to *Aquilapollenites* sp. cf. *A. quadrilobus*, normally associated with the Late Cretaceous and Paleocene. Survival of relict taxa in wetlands may explain other stratigraphic range extensions that might otherwise be attributed to recycling, giving a chronostratigraphic meaning to the concept of wetland vegetation as “intrazonal”. The modern redwood species, *Taxodium,* in wetlands of southeastern United States may be an example of such a relict survival. Similarly, A.R. Sweet (personal communication, 29 March 2010) has noted that relict “Maastrichtian” taxa preferentially occur in the earliest Paleocene in coaly shales and coals, suggesting that the swamp and swamp margin environment contributed to their survival.

TECTONIC IMPLICATIONS

The accumulation of sediment during the Late Eocene can be explained by subsidence on the fault block that hosts the Mallik 5L-38 well. If the Oligocene and Early Miocene ages, proposed herein for the 900 to 340 m interval are correct, it would imply continued subsidence on that fault block during that time. If the Sub-Iperk unconformity is represented at 340 m, it would imply cessation or attenuation of subsidence during the Middle and Late Miocene.

White (1999) concluded that recycled palynomorphs in Mallik 2L-38 indicated Late Eocene regional unroofing of Cretaceous rocks. Increasing regional erosion in the Early Miocene, likely tectonically driven, is suggested by this Mallik 5L-38 study. However, Plio-Pleisotocene erosion is likely dominated by glacial episodes.

SUMMARY

This study of Mallik 5L-38 complements the palynological investigation of the Mallik 2L-38 well (White, 2009). This study provides more detailed biostratigraphic information for the interval from surface to 900 m, considers the significance of sample processing in identifying the recycled and contemporaneous components of a palynological assemblage, reviews the use of ratios for paleoclimatology and describes the palynology, age and paleonvironmental results for coal samples from core in the 933 to 1082 m interval.

This study has detected a difference between the palynoflora in the +180 µm organic fraction and the kerogen organic fraction of a sample for strata from the interval 445 to 900 m. The +180 µm fraction holds palynomorhs that appear to be recycled, and their release by oxidation would affect the composition of the assemblage. It has been argued that an interpretable palynological signal, composed nonetheless of contemporaneous and recycled palynomorphs, can be obtained from the kerogen. The recycled palynomorphs in the kerogen and +180 µm assemblages contribute to the regional geological evidence of erosion. The need to separate the +180 µm and kerogen fractions may apply to only a limited stratigraphic interval in the Beaufort-Mackenzie Basin, and that interval has not been delimited by this study.

The following summarizes the biostratigraphic subdivisions and chronicles significant events identified in this study of the Mallik 5L-38 well. The lack of simple clarity in Beaufort-Mackenzie palynostratigraphy, particularly with regard to the Oligocene, shows that there is much to be learned, and these conclusions themselves must be reconsidered in light of further evidence.

0 - 270 m

Artemisia is the most distinctive marker in Mallik 5L-38 in the 0 to 270 m interval. *Artemisia* and the apparent sparsity of vegetation are consistent with a late Plio-Pleistocene age. The sediment is unconsolidated and the hole is extensively caved above 340 m.

270 - 340 m

Deposition of eroded material was a dominant process contributing to the strata between about 340 to 270 m. Glaciation, although not necessarily at continental scale, was an erosive force in the late Pliocene-Pleistocene. Glaciation could aggressively erode regional bedrock and rapidly deposited fine-grained, poorly consolidated, or ice-bonded sediment. Tectonism might also have been a contributing erosive factor. The base of this unit probably marks a significant erosional unconformity and it is probably the sub-Iperk regional erosional unconformity.

340 - 700 m

Compared to underlying strata, this interval records an increase in regional erosion, with a stepped increase in Sum of Recycled Palynomorphs at the base of this interval, and with a further increase in Unknowns and Undeterminables at the top. Within this unit, the increased comminution of recycled organic matter above 445 m and reduced competence of the penetrated rocks above 550 m argues for accelerated regional erosion and deposition at the site of modern Richards Island. *Tsuga* pollen, and the lack of evidence for a palynoflora indicating a Middle Miocene thermal maximum or an assemblage typical of the subsequent late Middle and Late Miocene decline of thermophiles suggest that this unit is of Early Miocene age. Hence, a major erosional unconformity is implied for the top of this unit. The increasing evidence of regional erosion probably indicates that a tectonic pulse began in the Early Miocene. The need to acetolyse kerogen samples below 550 m probably indicates some lithological change. There may be an event or disconformity/unconformity at 445 m and perhaps at 550 m, but the major unconformity is at the top of this unit.

700 - 900 m

The interval is thought to be of Oligocene age. Strata from 900 m to 850 m probably represent the Early Oligocene, and experimental climate proxy ratios generated in the Mallik 2L-38 study and in this study suggest that it is a cool interval with temperatures rising startigraphically upwards in this interval, but the following caveats must be heeded. The 850 to 700 m interval is though to be of Late Oligocene age, and probably indicative of the Late Oligocene (Chattian) warm period previously identified in the Arnak Member in Nuktak C-22 by Norris (1982, 1986) and which is also evident in the Ukalerk C-50 well (McNeil et al., 1982**).** The failure of the experimental ratios to match in the overlapping section of the 2L-38 and 5L-38 wells means that there is be more to be learned about this technique and the geological context in which it is applied. An explanation that seems probable with current knowledge is that, above 886 m, an increased degree of recycling has confused pollen ratios that behaved more coherently below that depth in the Mallik 2L-38 well. The onset of this pattern could be, in itself, an indicator of a new sedimentary/paleoenvironmental regime associated with global cooling in the earliest Oligocene.

Coals from core, 933.65 - 1081.90 m

Fourteen samples from coal bed cores in the 933.65 to 1081.90 m interval yielded palynological evidence and virtually eliminates the possibility that the palynomorphs were recycled. These beds can reasonably be correlated by depth to Mallik 2L-38 (within about ±10 m). Palynological assemblages from these coals allow a confident interpretation of age, paleoclimate, paleoenvironment, and may help explain stratigraphic range extensions.

The palynology, sedimentology, geochemical and organic matter analysis of Mallik 5L-38 and adjacent 2L-38 yield a consistent interpretation of a proximal to distal deltaic plain setting with a dominance of terrestrial organic matter, but with marine influence and incursions. This environment would support a rich local flora yielding *in situ* palynomorphs. The limited dinoflagellate and foraminiferal results from 2L-38 are compatible with this environmental setting and with a Late Eocene age.

Floral modernization in the Eocene deprives palynologists of much of the tool of morphological evolution of pollen and spores for detecting the passage of time. This study has relied on correlation to global paleoclimatic patterns as a significant line of evidence. Nonetheless, a problem with tracing biostratigraphic patterns that are driven by climatic change is that Oligocene and younger climates experienced many oscillations between warm and cold. Could the Chattian warm period be equivalent to the Eocene and the age of these coals be late Oligocene, not late Eocene? Three factors argue that these are not Oligocene strata: the presence of traditional palynomorph indicators of the Eocene, the degree of climatic warmth indicated by the palynomorphs and the declining trend of temperature indicated by the pollen ratios that follows the Late Eocene pattern. Were definitive evidence to be found indicating that the strata are Oligocene, a significant revision to standards in regional palynostratigraphy would be required.

The paleoclimate evidence based on modern relatives of taxa found in these coals suggests a minimum January mean monthly paleotemperature of -23° C, and July mean monthly temperatures of at least 13° C, but both were likely much warmer. These paleotemperatures are also consistent with an Eocene age.

The ecology of the wetlands may have been controlled locally by surface water flow and by wetland pH. Broader determinants may have been subsidence along listric faults and/or eustatic changes.

Wetlands appear to host relict taxa whose geographic or environmental ranges diminished to the point where they have have otherwise vanished from the regional pollen record. This mechanism emphasizes local environment as an important determinant of palynostratigraphic patterns.

Subsidence on the fault block hosting the Mallik 5L-38 well is inferred during the Late Eocene, Oligocene and Early Miocene. Cessation or attenuation of subsidence during the Middle and Late Miocene is also inferred.

Questions resulting from this study

The assumptions used, and the work reported above give rise to several questions, which could be addressed by future work.

1. Is it a valid assumption that is applied here and in the study of Mallik 2L-38; i.e., that recycling is relatively chaotic, and that non-chaotic patterns in the palynoflora indicate biologically-driven biostratigraphic patterns? How can one assess this assumption?

2. What is the stratigraphic and geographic extent of the occurrence of recycled flora identified in the +180 μm fraction? Is it restricted to the strata penetrated in the 445 to 900 m interval of the Mallik wells or is it stratigraphically more extensive? Wherever such recycling

occurs, a sample which has been fully oxidized will report a different, and probably a taxonomically richer flora than the comparable kerogen preparation. If recycling is from Cretaceous or older rocks, it does not present a great identification problem, except for long-ranging taxa like the Taxodiaceae-Cupressaceae-Taxaceae. If recycling is from older Paleogene rocks into younger Paleogene or Neogene rocks, it presents a significant problem in recognizing the recycled fraction and separating recycling from legitimate range extensions. Using “kerogen” preparations (as defined here) helps to alleviate the recycling detection problem, but is not a guarantee that one is analysing the contemporaneous flora. One may get a good idea of the overall recycled state of an assemblage, but may never be able to prove that any individual taxon is or is not recycled. From an analytic standpoint recycling presents a continuous challenge, but the recycling patterns are evidence of regional landscape processes such as tectonism and glaciation.

3. What size of cutting sample is required to get adequate representation of the palynoflora in the kerogen preparation to reduce the statistical vagaries of palynomorph representation and the time required for analysis? Samples of 13 to 20 grams were used in this study, but should have been larger. The proportion of fine- and coarse-grained rocks in the strata penetrated, and the availablity of larger core or cutting samples limits this objective.

4. Why is the palynostratigraphic representation of the Oligocene taxonomically inconsistent amongst the several studies? Is it because of insufficient numbers of palynomorphs in the residue so that the taxonomic diversity of the palynoflora is not well represented in each study? Rarefaction curves for the assemblages could determine if the assemblages are under-saturated with species, as they are most likely. Higher palynomorph counts are probably required, but may be difficult to achieve if sample volumes of cuttings are limited. Does the presence of recycled palynomorphs in the assemblages contribute to the inconsistency of Oligocene representation? To what degree does the variation in proximity to the continent amongst study sites influence the consistency of representation of the palynofloras?

5. A question regarding the comparability of this study to the 2L-38 study is whether palynomorphs leaked from +180 µm fraction into the kerogen preparation in the 2L-38 study. A comparison of the processing techniques and further experimentation indicates that the leakage would be minimal but cannot be ruled out. However, the ratios of selected taxa do not match nicely in the section of overlapping analysis between 900 and 670 m, and one possible explanation is that leakage of recycled taxa into the kerogen did indeed happen.

6. Organic petrography and fluorescence microscopy may shed light on the composition and origin of the +180 µm fraction . Knowledge of the stratigraphic interval for which the +180 μm fraction should be separated is required.

7. If the Mackenzie River delta area was producing even a moderate amount of pollen area in the mid-Cenozoic, why are pollen concentrations so low? Does it indicate a high sedimentation rate, or is it just a product of working with cuttings in a dominantly fluvial

sequence? If only a few fine-grained beds occur amongst coarser beds, the average pollen productivity in a cuttings sample would be low.

8. Are there identifiable associations amongst palynomorph taxa that represent environmental and climatic conditions? Recognition of such associations would help to understand the biostratigraphic signal.

Answers to these questions will help to refine palynostatigraphy in the Beaufort-Mackenzie Basin, and in so doing will improve our understanding of both this frontier hydrocarbon basin and of high latitude environmental change in the late Cenozoic.

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LIST OF FIGURES

Figure 1. Location of wells and sections.

Figure 2. Mallik 5L-38 caliper log, 100 to 650 m.

Figure 3. Mallik 5L-38 palynomorphs recorded in kerogen and +180 µm fractions from cutting samples of 105 to 900 m depth, and from coal core samples from 940 to 1082 m depth. Palynomorphs are plotted alphabetically and by relative abundance and by group. Blue represents the kerogen fraction and coal core samples (Analyst "JMW"). Green represents oxidized preparations of the + 180 µm fraction from 450 m to 900 m (analyst "Fract"), that are plotted 3.66 m below their true depth. This relative abundance plot presents the occurrences of taxa along with the qualifiers, "?", to denote questioned identifications.

Figure 4. Axes 1 and 2 from correspondence analysis results of Mallik 5L-38 pollen and filicale spore taxa, samples from 450 to 900 m with paired kerogen +180 µm analyses that are designated as 3.66 m below their true depth. Samples 483.66 m and 513.66 m are omitted, as are taxa with only one occurrence.)

Figure 5. Axes 1 and 3 from correspondence analysis results of Mallik 5L-38 pollen and filicale spore taxa, samples from 450 to 900 m with paired kerogen +180 µm analyses that are designated as 3.66 m below their true depth. Samples 483.66 m and 513.66 m are omitted, as are taxa with only one occurrence. The dispersion of the data on Axis 3 allows the sample distribution on Axis 1 to be seen with less overprinting of data points and labels.

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TABLES

Table 1. Selected drilling history records of biostratigraphic significance for Mallik 5L-38 (data from Canadian Petroleum Engineering, 2002; comments refer to intervals between depths on left, and events at depths on right)

INTERVAL				EVENT	
Inter-val Depth m (KB)	**Bit Size (mm)**	**Borehole Diameter (mm)**	**Comment on Interval**	**Event Depth m (KB)**	**Comment on Event**
				102	top of *Platform Express: Cement Volume Log*
				24	base of conductor
	311		no log of diameter		
116				**116**	base permafrost casing
	311	> 620	extensive erosion		
320				**320**	change in borehole erosion
	311	variable > and < 620	considerable erosion with non-eroded sections		
560				**560**	change in borehole erosion
				573	cleaned mud tanks, changed shaker screens
	311	<400	minor erosion but without major washouts		

				620	approx. base of permafrost; change in erosion probably due to change in permafrost
650	—			**650**	change in logs
				675	top of *Integrated Hole/Cement Volume Summary Log*
676	—			**676**	base of casing
			no caliper log		
677	—				
	311	~<325	erosion from circulation and cement; not caved to cuttings below?		
687	—			**687**	drilled to here before setting casing; bit size change to 222 mm
	222	normally <265	little erosion		
762	—			**762**	change in borehole erosion
	222	<230	minimal erosion		
885.6	—			**885.6**	top of coring
			cored interval		
1151	—			**1151**	base of coring
1166				**1166**	TD

Table 2. Sample preparation techniques for Mallik 2L-38 and 5L-38.

Processing / Well	**2L-38**	**5L-38**	
Sequential step	kerogen	kerogen fraction	+180 µm fraction
1. Weigh sample	**x**	**x**	
2. Add Exotic *Lycopodium* spike	**x**	**x**	
3. HCl	**x**	**x**	
4. HF		**x**	
5. Screen - coarse mesh	180 µm (discard any +180 µm fraction)	180 µm (450 to 900m) →	residue on screen
6. Oxidized (5 minutes of hot Schulze solution)			**x**
7. Neutralization by ammonium hydroxide			**x**
8. Screen - coarse mesh			resieved at 180 µm by hand
8. Screen - fine mesh	7 µm by ultrasound	10 µm by hand	10 µm by hand
10. Cleaning by light Javex	**x**		
11. Neutralization by ammonium hydroxide	**x**		
12. Acetolysis		550 m and below	
13. Kerogen slide	**x**	**x**	
14. Oxidized slide			**x**

Table 3. Comparison of palynomorph assemblages from kerogen and acetolysed kerogen preparations for Mallik 5L-38 samples 580, 590 and 600 m.

Mallik 5L-38, 580 m

Taxon	P4672-95 Kerogen			P4672-95c Acetolysis			Difference	
	Count	%	Count/ Spike	Count	%	Prop. Count/ Spike	Absolute % Diff.	Absolute Prop. Diff.
Lycopodium Spike	53.0			119.0				
Alga	1.0	2.9	0.02	1.0	1.6	0.01	1.2	0.01
Anatolinites sp.				1.0				
Alnus 4-porate				2.0	3.2	0.02	3.2	0.02
Alnus 5-porate	1.0	2.9	0.02	1.0	1.6	0.01	1.2	0.01
Alnus 6-porate				1.0				
Betula <= 20 µm				2.0	3.2	0.02	3.2	0.02
Betula >20 µm								
Cedrus?								
Corylus -type								
Deltoidospora sp.				2.0	3.2	0.02	3.2	0.02
Dinoflagellate indet.								
Ericales	1.0	2.9	0.02				2.9	0.02
Fractisporonites sp.	1.0							
Fungal hyphae								
Inapertisporites dubius	3.0	8.6	0.06				8.6	0.06
Inapertisporites sp.(fungal)	1.0							
Larix/Pseudotsuga?				4.0	6.5	0.03	6.5	0.03
*Laevigatosporite*s sp.	1.0	2.9	0.02	2.0	3.2	0.02	0.4	0.00
Liliacidites								
Osmunda sp.								
Paraalnipollenties alterniporus?				1.0				
Picea sp.								
Pinus sp.				4.0	6.5	0.03	6.5	0.03
Pinaceae	2.0	5.7	0.04	4.0	6.5	0.03	0.7	0.00
Polyadosporites sp.								
Pterocarya sp.				1.0				
Recycled Palynomorphs	5.0	14.3	0.09	8.0	12.9	0.07	1.4	0.03
*Retitricolpite*s sp.				1.0				
Sciadopitys?								
Sparganium sp.				1.0				
Sphagnum sp.	1.0	2.9	0.02	2.0	3.2	0.02	0.4	0.00
Taxodiaceae-Cupressaceae-Taxaceae	5.0	14.3	0.09	8.0	12.9	0.07	1.4	0.03
Tricolpites sp.								

Triporopollenties sp.				3.0	4.8	0.03	4.8	0.03
Tsuga canadensis -type								
Ulmus -type								
Undeterminable	13.0	37.1	0.25	13.0	21.0	0.11	16.2	0.14
Sum Palynomorphs	**35.0**	**100.0**	**0.66**	**62.0**	**100.0**	**0.52**		**0.14**
Species Count	**12.0**			**20.0**				
Pinaceae/T-C-T	**0.25**			**1.00**				

Mallik 5L-38, 590 m

Taxon	**P4672-97 Kerogen**			**P4672-97c Acetolysis**			**Difference**	
	Count	**%**	**Count/ Spike**	**Count**	**%**	**Count/ Spike**	**Absolute % Diff.**	**Absolute Prop. Diff.**
Lycopodium Spike	92.0			141.0				
Alga	1.0	2.0	0.01				2.0	0.01
Alnus 4-porate				1.0	1.6	0.01	1.6	0.01
Alnus 5-porate	2.0	4.1	0.02	1.0	1.6	0.01	2.5	0.01
Betula <= 20 µm								
Betula >20 µm				2.0	3.2	0.01	3.2	0.01
Cedrus?								
Corylus -type				1.0	1.6	0.01	1.6	0.01
Deltoidospora sp.	1.0	2.0	0.01	4.0	6.5	0.03	4.4	0.02
Dinoflagellate indet.				1.0				
Ericales								
Fungal hyphae								
Inapertisporites dubius	3.0	6.1	0.03	1.0	1.6	0.01	4.5	0.03
Inapertisporites sp.(fungal)	1.0			3.0				
Larix/Pseudotsuga?	1.0	2.0	0.01				2.0	0.01
Laevigatosporites sp.				4.0	6.5	0.03	6.5	0.03
Liliacidites								
Osmunda sp.								
Picea				2.0	3.2	0.01	3.2	0.01
Pinus	5.0	10.2	0.05	2.0	3.2	0.01	7.0	0.04
Pinaceae	2.0	4.1	0.02	2.0	3.2	0.01	0.9	0.01
Polyadosporites sp.								
Recycled Palynomorphs	3.0	6.1	0.03	9.0	14.5	0.06	8.4	0.03
Sciadopitys?								
Sphagnum sp.	3.0	6.1	0.03	1.0	1.6	0.01	4.5	0.03
Taxodiaceae-Cupressaceae-Taxaceae	1.0	2.0	0.01	3.0	4.8	0.02	2.8	0.01
Tricolpites sp.	1.0	2.0	0.01					
Triporopollenties sp.	1.0	2.0	0.01	3.0	4.8	0.02	2.8	0.01
Tsuga canadensis -type								
Ulmus -type								
Undeterminable	24.0	49.0	0.26	22.0	35.5	0.16	13.5	0.10
Sum Palynomorphs	**49.0**	**100.0**	**0.53**	**62.0**	**100.0**	**0.44**		**0.09**

Species Count	**15.0**	**18.0**	
Pinaceae/T-C-T	**1.75**	**1.50**	

Mallik 5L-38, 600 m

Taxon	**P4672-99 Kerogen**			**P4672-99c Acetolysis**			**Difference**	
	Count	%	**Count/ Spike**	**Count**	%	**Count/ Spike**	**Absolute % Diff.**	**Absolute Prop. Diff.**
Lycopodium Spike	38.0			118.0				
Alga				2.0	2.1	0.02	2.1	0.02
Alnus 4-porate	2.0	7.1	0.05	7.0	7.3	0.06	0.1	0.01
Alnus 5-porate	1.0	3.6	0.03	2.0	2.1	0.02	1.5	0.01
Betula <= 20 µm								
Betula >20 µm				3.0	3.1	0.03	3.1	0.03
Cedrus?				1.0	1.0	0.01	1.0	0.01
Corylus -type				1.0	1.0	0.01	1.0	0.01
Deltoidospora sp.	1.0	3.6	0.03	4.0	4.2	0.03	0.6	0.01
Ericales	1.0	3.6	0.03	2.0	2.1	0.02	1.5	0.01
Fungal hyphae				1.0	1.0	0.01	1.0	0.01
Inapertisporites dubius	1.0	3.6	0.03	3.0	3.1	0.03	0.4	0.00
Larix/Pseudotsuga?				1.0	1.0	0.01	1.0	0.01
Laevigatosporites sp.	2.0	7.1	0.05	6.0	6.3	0.05	0.9	0.00
Liliacidites				1.0	1.0	0.01	1.0	0.01
Osmunda sp.				1.0	1.0	0.01	1.0	0.01
Picea sp.				2.0	2.1	0.02	2.1	0.02
Pinus sp.				2.0	2.1	0.02	2.1	0.02
Pinaceae	4.0	14.3	0.11	8.0	8.3	0.07	6.0	0.04
Polyadosporites sp.	1.0	3.6	0.03				3.6	0.03
Recycled Palynomorphs	3.0	10.7	0.08	8.0	8.3	0.07	2.4	0.01
Sciadopitys?				1.0	1.0	0.01	1.0	0.01
Sphagnum sp.				1.0	1.0	0.01	1.0	0.01
Taxodiaceae-Cupressaceae-Taxaceae	3.0	10.7	0.08	1.0	1.0	0.01	9.7	0.07
Triporopollenties sp.	1.0	3.6	0.03	2.0	2.1	0.02	1.5	0.01
Tsuga canadensis -type				2.0	2.1	0.02	2.1	0.02
Ulmus -type				1.0	1.0	0.01	1.0	0.01
Undeterminable	8.0	28.6	0.21	33.0	34.4	0.28	5.8	0.07
Sum Palynomorphs	**28.0**	**100.0**	**0.74**	**96.0**	**100.0**	**0.81**		**0.08**
Species Count	**12.0**			**25.0**				
Pinaceae/T-C-T	**1.00**			**3.00**				

Table 4. Summation categories and references for kerogen taxa identified in Mallik 5L-38.

Taxa summation categories and references			**Recycled Palynomor**	**Marine/ Aquatic Palynomorphs**			**Terrestrial Palynomorphs**					
"Kerogen" taxa	**Author/Reference**	**Affinity**	**Recycled**	**Dinoflagellates**	**Algae**	**Foraminiferal/Scolecodonts**	**Fungi**	**Bryophte**	**Ferns and Allies**	**Gymnosperms**	**Angiosperms**	**Temperate Angiosperms**
Micrhystridium sp.		AC			1							
Veryhachium sp.		AC	1									
Ovoidites ligneolus	(Potonié) Potonié 1966	AL			1							
Sigmopollis carbonis	(Newman) Srivastava 1984	AL			1							
Sigmopollis sp.		AL			1							
Algae spp.		AL IN			1							
Dinoflagellate indet.		DC	1	?								
Filisphaera filifera	Bujak 1984	DC		1								
Labyrinthodinium truncatum	Piasecki 1980	DC		1								
Odontochitina operculata	Deflandre & Cookson 1955	DC	1	?								
Peridinioid dinoflagellate		DC		1								
Polysphaeridium zoharyi	(Rossignol) Bujak et al.1980	DC	?	1								
Spiniferites sp.		DC		1								
Microforaminiferal test lining		FO				1						
Brachysporisporites sp.		FU					1					
Dicellaesporites sp.		FU					1					
Diporisporites sp.		FU					1					
Foveodiporites sp.		FU					1					
Fractisporonites sp.		FU					1					
Fungi hyphae		FU					1					
Hypoxylonites sp.		FU					1					
Inapertisporites sp.		FU					1					
Involutisporonites sp.		FU					1					
Lacrimasporonites sp.		FU					1					
Monoporisporites sp.		FU					1					
Multicellaesporites sp.		FU					1					
Multicellites sp.		FU					1					
Papulosporonites sp.		FU					1					
Polyadosporites spp.		FU					1					
Reduviasporonites sp.		FU					1					
Striadiporites inflexus	(Ke & Shi) Norris 1986	FU					1					

Striadiporites multistriatus	(Ke & Shi) Norris 1986	FU					1					
Trichopeltina sp.		FU					1					
Unknown spp.		FU					1					
Scolecodont undiff.		MP				1						
Abies sp.		SP								1		
Acer sp.		SP										1
Alnus 3-porate		SP									1	
Alnus 4-porate		SP									1	
Alnus 5-porate		SP									1	
Alnus 6-porate		SP									1	
Apiaceae undiff.		SP									1	
Appendicisporites sp.		SP	1									
Araucariacites australis	Cookson 1947	SP	1									
Arecipites symmetricus	Krutzsch 1970	SP									1	
Artemisia sp.		SP									1	
Asteraceae undiff.		SP									1	
Baculatisporites primarius crassiprimarius	Krutzsch 1967	SP							1			
Baculatisporites quintus	(Thompson and Pflug) Krutzsch sensu Norris 1986	SP							1			
Baculatisporites sp.		SP							1			
Betula <= 20 um		SP									1	
Betula >20 um		SP									1	
Callistopollenites sp.		SP	1									
Carya sp.		SP										1
Caryophyllaceae undiff.		SP									1	
Chenopodiineae undiff.		SP									1	
Cicatricosisporites australiensis	(Cookson) Potonié 1956	SP	?						1			
Cicatricosisporites hallei	Delcourt & Sprumont 1955	SP	?						1			
Cicatricosisporites paradorogensis	Krutzsch 1959	SP	?						1			
Cicatricosisporites sp.		SP	?						1			
Cicatricosisporites spiralis	Singh 1971	SP	?						1			
Classopollis classoides	Pflug emend. Pocock & Jansonius	SP	1									
Corylus-type		SP									1	
Deltoidospora sp.		SP	?						1			
Diervilla/Weigela sp.		SP									1	
Distaltriangulisporites perplexus	(Singh) Singh 1971	SP	1									
Equisetum sp.		SP							1			
Ericales undiff.		SP									1	
Gleicheniidites senonicus	Ross 1949	SP	1						1			
Hamulatisporis sp.		SP	?						1			
Ilex-type		SP										1

Inaperturopollenites dubius	(Potonié) Thomson & Pflug 1953	SP	?							1		
Iridaceae/Liliaceae sp.		SP									1	
Klukisporites foveolatus	Pocock 1964	SP	1						?			
Kurtzipites sp.		SP	1									
Labrapollis sp.		SP									1	
Laevigatosporites sp.		SP							1			
Larix/Pseudotsuga-type		SP								1		
Lycopodium annotinum/complanatum		SP							1			
Lycopodium sp.		SP							1			
Lycopodium spike		SP										
Magnolia sp.		SP										1
Mallik5L-38 unknown 01		SP									1	
Mallik5L-38 unknown 02		SP									1	
Mallik5L-38 unknown 04		SP									1	
Mallik5L-38 unknown 05		SP									1	
Momipites wyomingensis	Nichols & Ott 1978	SP	?								1	
Onagraceae undiff.		SP									1	
Osmunda sp.		SP							1			
Paraalnipollenites alterniporus	(Simpson) Srivastava 1975	SP	1								?	
Picea sp.		SP								1		
Pinaceae undiff.		SP								1		
Pinus koraiensis-type	of White & Ager 1994	SP								1		
Pinus sp.		SP								1		
Pistillipollenites macgregorii	Rouse 1962	SP	1								?	
Poaceae undiff.		SP									1	
Podocarpus -type		SP								1		
Polypodiaceae-Dennstaedtiaceae form 1	of Martin & Rouse 1966	SP							1			
Polypodiaceae-Dennstaedtiaceae form 2	of Martin & Rouse 1966	SP							1			
Pterocarya sp.		SP										1
Recycled palynomorphs		SP	1									
Reticulosporis sp.		SP							1			
Retimonocolpites sp.		SP									1	
Retitricolpites sp.		SP									1	
Sciadopitys sp.		SP								1		
Selaginella microdendron-type	see Tryon & Lugardon 1991	SP							1			
Selaginella selaginoides	see Tryon and Lugardon 1991	SP							1			
Selaginella sp.		SP							1			
Shepherdia canadensis		SP									1	
Sparganium sp.		SP									1	
Sphagnum sp.		SP	?					1				
Stereisporites	(Wilson & Webster)	SP	?					1				

antiquasporites	Dettmann 1963											
Stereisporites maximalis	Krutzsch 1963	SP	?					1				
Stereisporites microgranulus	sensu Norris 1986	SP	?					1				
Taxodiaceae-Cupressaceae-Taxaceae		SP	?							1		
Tetrad pollen (scabrate)		SP									1	
Tetraporate spp.		SP									1	
Tilia-type	of White & Ager 1994	SP										1
Triatriopollenites granilabratus	(Stanley) Norton in Norton & Hall 1969	SP	1								?	
Triatriopollenites pulcher	(Simpson) Parsons 2000	SP	1								?	
Tricolpites sp.		SP									1	
Tricolpopollenites sp.		SP									1	
Tricolporopollenites sp.		SP									1	
Triporate type D of Parsons 2000	of Parsons 2000	SP	?								1	
Triporopollenites sp.		SP									1	
Tsuga canadensis -type	of White & Ager 1994	SP								1		
Tsuga sp.		SP								1		
Tubuliflorae undiff.		SP									1	
Ulmus-type	of White & Ager 1994	SP										1
Undeterminable spp.		SP										
Unknown sp. A		SP										
Unknown spp.		SP										
Verrucosisporites obscurilaesuratus	Pocock 1962	SP							1			
Vitreisporites pallidus	(Reissinger) Nilsson 1958	SP										
AC - Acritarch, ALIN -Algae, DC - Dinoflagellate, FO - Foraminifera, FU - Fungus, MP - Miscellaneous Palynomorph, SP - Spore or Pollen												

Table 5. Correspondence analysis output with samples and taxa ordinated on Axis 1 by sample and taxa scores.

```
CORRESPONDENCE ANALYSIS by Multi-Variate Statistical Package, v. 3.13m, Kovach
Computing Services, 2004.
Data file - C:\Data\Mallik5L-38\Mallik5L-38export.mvs
Imported data
Analysis begun: Tuesday, December 07, 2004 4:30:01 PM
Analysing 74 variables x 90 cases
67 variables and 2 cases have been dropped from original data
Tolerance of eigenanalysis set at 1E-007
Cyclic Jacobi algorithm constrained to 10 axes
No adjustment of scores
Eigenvalues
                Axis 1 Axis 2 Axis 3 Axis 4 Axis 5 Axis 6 Axis 7 Axis 8 Axis 9 Axis 10
Eigenvalues     0.25   0.179  0.169  0.134  0.131  0.12   0.116  0.11   0.107  0.1
Percentage      7.581  5.42   5.14   4.066  3.966  3.645  3.511  3.328  3.252  3.042
Cum. Percent.   7.581  13.002 18.141 22.207 26.173 29.818 33.329 36.657 39.909 42.95
```

Samples sorted by Axis 1 scores				**Taxa sorted by Axis 1 scores**		
Sample depth (m)	**Groups**	**Axis 1**		**Taxa**		**Axis 1**
543.7	+180 µm	-2.139		*Castanea* -type		-3.489
653.7	+180 µm	-2.138		Sum *Celtis*		-3.229
863.7	+180 µm	-2.077		*Pistillipollenites macgregorii*		-2.903
833.7	+180 µm	-1.851		*Podocarpus* -type		-2.87
853.7	+180 µm	-1.744		*Triatriopollenites pulcher*		-2.798
643.7	+180 µm	-1.665		*Hazaria sheopiarii*		-2.74
843.7	+180 µm	-1.637		*Pachysandra/Sarcococca* *(Erdtmanipollis procumbentiformis)*		-2.708
713.7	+180 µm	-1.592		*Pristinuspollenites* sp.		-2.608
693.7	+180 µm	-1.576		*Cranwellia* sp.		-2.531
703.7	+180 µm	-1.555		Sum *Azonia*		-2.296
683.7	+180 µm	-1.294		Sum *Distaltriangulisporites*		-2.219
893.7	+180 µm	-1.164		Apiaceae undiff.		-2.167
743.7	+180 µm	-1.151		*Paraalnipollenites alterniporus*		-2.123
593.7	+180 µm	-1.147		*Striatocorpus* sp.		-1.995
898.7	+180 µm	-1.132		*Sciadopitys* sp.		-1.993
823.7	+180 µm	-1.099		*Rousea* sp.		-1.916
803.7	+180 µm	-1.033		Sum *Wodehouseia*		-1.909
723.7	+180 µm	-1.031		*Retimonocolpites* sp.		-1.774
573.7	+180 µm	-0.966		*Hamulatisporis* sp.		-1.675
903.7	+180 µm	-0.961		*Retitricolpites* sp.		-1.633
473.7	+180 µm	-0.954		Rosaceae undiff.		-1.603

633.7	+180 µm	-0.861		*Retitricolporopollenites* sp.		-1.556
583.7	+180 µm	-0.857		*Appendicisporites* sp.		-1.546
813.7	+180 µm	-0.824		*Tricolpopollenites* sp.		-1.514
783.7	+180 µm	-0.823		Sum *Stereisporites*		-1.49
873.7	+180 µm	-0.794		*Triatriopollenites granilabratus*		-1.447
793.7	+180 µm	-0.779		*Carya* sp.		-1.338
623.7	+180 µm	-0.701		Sum *Cicatricosisporites*		-1.293
733.7	+180 µm	-0.67		Iridaceae/Liliaceae sp.		-1.283
673.7	+180 µm	-0.657		*Vitreisporites pallidus*		-1.271
663.7	+180 µm	-0.6		Sum *Gleicheniidites*		-1.247
773.7	+180 µm	-0.558		Sum Polypod.-Dennstaedt.		-1.219
533.7	+180 µm	-0.407		*Ilex* -type		-1.205
503.7	+180 µm	-0.37		*Quercus* sp.		-1.159
603.7	+180 µm	-0.234		Sum *Lycopodium*		-0.925
523.7	+180 µm	-0.141		*Pinus koraiensis* -type		-0.849
553.7	+180 µm	-0.127		*Osmunda* sp.		-0.626
763.7	+180 µm	-0.029		*Sparganium* sp.		-0.367
563.7	+180 µm	0		*Tilia* -type		-0.203
660	kerogen	0.073		Ericales undiff.		-0.16
753.7	+180 µm	0.085		*Ulmus* -type		-0.095
493.7	+180 µm	0.102		*Sphagnum* sp.		-0.053
500	kerogen	0.167		Tetrad pollen (scabrate)		-0.011
613.7	+180 µm	0.185		*Tricolpites* sp.		0.02
720	kerogen	0.298		Taxodiaceae-Cupressaceae-Taxa. undiff.		0.094
810	kerogen	0.404		*Magnolia* sp.		0.101
640	kerogen	0.42		Sum *Selaginella*		0.122
463.7	+180 µm	0.431		*Inaperturopollenites dubius*		0.148
890	kerogen	0.52		*Laevigatosporites* sp.		0.161
900	kerogen	0.54		*Triporopollenites* sp.		0.287
453.7	+180 µm	0.563		*Momipites wyomingensis*		0.323
520	kerogen	0.593		*Picea* sp.		0.339
690	kerogen	0.593		*Pinus* sp.		0.339
860	kerogen	0.595		*Deltoidospora* sp.		0.398
480	kerogen	0.627		*Larix/Pseudotsuga* -type		0.562
600	kerogen	0.647		Sum *Alnus*		0.817
580	kerogen	0.668		*Pterocarya* sp.		0.821
830	kerogen	0.698		Pinaceae undiff.		0.881
730	kerogen	0.702		*Tsuga canadensis* -type		0.887
895	kerogen	0.732		*Baculatisporites quintus*		0.937
870	kerogen	0.744		*Tricolporopollenites* sp.		0.97
840	kerogen	0.862		*Acer* sp.		0.978
800	kerogen	0.875		*Betula* >20 um		1.065
630	kerogen	0.881		*Kurtzipites* sp.		1.186
570	kerogen	0.885		*Corylus* -type		1.292

700	kerogen	0.885		*Abies* sp.		1.324
850	kerogen	0.938		*Tsuga* sp.		1.349
820	kerogen	0.941		*Baculatisporites primarius crassiprimarius*		1.49
560	kerogen	0.947		Tetraporate spp.		1.623
780	kerogen	0.959		*Arecipites symmetricus*		1.655
790	kerogen	0.968		Chenopodiineae undiff.		1.657
740	kerogen	0.973		*Betula <= 20 um*		1.794
750	kerogen	0.973		*Shepherdia canadensis*		1.988
450	kerogen	0.977		*Classopollis classoides*		2.174
540	kerogen	0.99				
590	kerogen	1.013				
470	kerogen	1.044				
620	kerogen	1.045				
530	kerogen	1.065				
550	kerogen	1.072				
710	kerogen	1.089				
490	kerogen	1.098				
510	kerogen	1.098				
770	kerogen	1.103				
650	kerogen	1.178				
610	kerogen	1.225				
760	kerogen	1.263				
670	kerogen	1.28				
680	kerogen	1.325				
460	kerogen	1.331				

Table 6. Age range of selected, probably recycled palynomorphs in Mallik 5L-38 well, sorted by depth.

Age range of selected, probably recycled palynomorphs in Mallik 5L-38 well, sorted by depth							
		Approximate age from literature		**Approximate age (Ma)**			
Depth (m)	**Taxon**	**Lower**	**Upper**	**Lower age (Ma)**	**Upper age (Ma)**	**Reference**	**Location**
110	*Pistillipollenites macgregorii*	Chron 26n	Late Eocene	60	34	11-ARS-1998; White, in press	Ellesmere Island, Beaufort-Mackenzie region
185	*Classopollis classoides*	Early Triassic	Paleocene	245	55	White et al., 2002; A.R. Sweet, pers. comm., 2004	global, Alberta
210	*Classopollis classoides*	Early Triassic	Paleocene	245	55	White et al., 2002; A.R. Sweet, pers. comm., 2005	global, Alberta
370	*Paraalnipollenites alterniporus*	Paleocene	Late Eocene, ?Oligocene	65	34	Rouse, 1977; Ioannides & McIntyre, 1980; Long & Sweet, 1994; Parsons, 2000; Palynodata Inc. & White, 2008	Eurasia & N. America, N of 20°
370	*Vitreisporites pallidus*	$J1_3$	Campanian	183	70	Pocock, 1970a,b; A.R. Sweet, pers. comm., 2004	Alberta
440	*Paraalnipollenites alterniporus*	Paleocene	Late Eocene, ?Oligocene	65	34	Rouse, 1977; Ioannides & McIntyre, 1980; Long & Sweet, 1994; Parsons, 2000; Palynodata Inc. & White, 2008	Eurasia & N. America, N of 20°
460	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
473.66	*Wodehouseia spinata*	Chron 30n	Chron 28n	66	62	11-ARS-1998	Alberta
473.66	*Cranwellia* sp.	late Campanian	Paleocene	76	56	Nichols & Sweet, 1993	Alberta
473.66	*Azonia* sp.	?Coniacian	Late Maastrichtian	89	65	Nichols & Sweet, 1993	western interior N. America
483.66	*Paraalnipollenites alterniporus*	Paleocene	Late Eocene, ?Oligocene	65	34	Rouse, 1977; Ioannides & McIntyre, 1980; Long & Sweet, 1994; Parsons, 2000; Palynodata Inc. & White, 2008	Eurasia & N. America, N of 20°
483.66	*Wodehouseia* sp.	late Maastrichtian	Paleocene	67	55	Nichols & Sweet, 1993	Alberta
513.66	*Wodehouseia* sp.	late Maastrichtian	Paleocene	67	55	Nichols & Sweet, 1994	Alberta
513.66	*Kurtzipites* sp.	Maastrichtian	Early Paleocene	71	61	Nichols & Sweet, 1993; A.R. Sweet, pers. comm., 2004	Yukon/ NWT
533.66	*Vitreisporites pallidus*	$J1_3$	Campanian	183	70	Pocock, 1970a,b; A.R. Sweet, pers. comm., 2004	Alberta
543.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2000	NWT
543.66	*Paraalnipollenites alterniporus*	Paleocene	Late Eocene, ?Oligocene	65	34	Rouse, 1977; Ioannides & McIntyre, 1980; Long & Sweet, 1994; Parsons, 2000; Palynodata Inc. & White, 2008	Eurasia and N. America, N of 20°
543.66	*Hazaria sheopiariae*	Campanian	Paleocene	84	55	Srivastava 1971; A.R. Sweet, pers. comm., 2004	Alberta

553.66	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
553.66	*Hazaria sheopiariae*	Campanian	Paleocene	84	55	Srivastava 1971; A.R. Sweet, pers. comm., 2004	Alberta
560	*Classopollis classoides*	Early Triassic	Paleocene	245	55	White et al., 2002; A.R. Sweet, pers. comm., 30Dec2006	global, Alberta
573.66	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 30Dec2006	Wyoming
573.66	*Hazaria sheopiariae*	Campanian	Paleocene	84	55	Srivastava 1971; A.R. Sweet, pers. comm., 2004	Alberta
583.66	*Vitreisporites pallidus*	$J1_3$	Campanian	183	70	Pocock, 1970a,b; A.R. Sweet, pers. comm., 2004	Alberta
603.66	*Distaltriangulisporites perplexus*	Valanginian	Campanian	140	70	Burden & Hills, 1989; Payenberg et al, 2003	Alberta
610	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
610	*Classopollis classoides*	Early Triassic	Paleocene	245	55	White et al., 2002; A.R. Sweet, pers. comm., 2004	global, Alberta
630	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
653.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2001	NWT
653.66	*Distaltriangulisporites irregularis*	Valanginian	Campanian	140	70	Burden & Hills, 1989; Payenberg et al, 2002	Alberta
653.66	*Distaltriangulisporites perplexus*	Valanginian	Campanian	140	70	Burden & Hills, 1989; Payenberg et al, 2004	Alberta
653.66	*Appendicisporites* sp.	Berriasian	Cenomanian	145	93	Burden & Hills, 1989; Singh, 1983	Alberta
660	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
660	*Distaltriangulisporites perplexus*	Valanginian	Campanian	140	70	Burden & Hills, 1989; Payenberg et al, 2005	Alberta
660	*Vitreisporites pallidus*	$J1_3$	Campanian	183	70	Pocock, 1970a,b; A.R. Sweet, pers. comm., 2004	Alberta
673.66	*Azonia pulchella*	Upper Santonian	Lower Maastrichtian	85	83	Wiggins, 1976	Alaska
673.66	*Vitreisporites pallidus*	$J1_3$	Campanian	183	70	Pocock, 1970a,b; A.R. Sweet, pers. comm., 2004	Alberta
683.66	*Tigrisporites* sp.	$J2_1$	Cenomanian	172	93	Pocock, 1970a,b; Singh, 1971, 1983	Alberta
683.66	*Vitreisporites pallidus*	$J1_3$	Campanian	183	70	Pocock, 1970a,b; A.R. Sweet, pers. comm., 2004	Alberta
690	*Kurtzipites* sp.	Maastrichtian	Early Paleocene	71	61	Nichols & Sweet, 1993; A.R. Sweet, pers. comm., 2004	Yukon/ NWT
690	*Appendicisporites* sp.	Berriasian	Cenomanian	145	93	Burden & Hills, 1989; Singh, 1984	Alberta
693.66	*Cranwellia* sp.	late Campanian	Paleocene	76	56	Nichols & Sweet, 1994	Alberta
693.66	*Azonia cribrata*	Assemblage 6, late Campanian	Assemblage 6, late Campanian	78	70	Nichols & Sweet, 1993	Bonnet Plume & Brackett basins
703.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2002	NWT
713.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2003	NWT
720	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
720	*Paraalnipollenites alterniporus*	Paleocene	Late Eocene, ?Oligocene	65	34	Rouse, 1977; Ioannides & McIntyre, 1980; Long & Sweet, 1994; Parsons, 2000; Palynodata Inc. & White, 2008	Eurasia & N. America, N of 20°
733.66	*Azonia* sp.	?Coniacian	Late Maastrichtian	89	65	Nichols & Sweet, 1994	western interior N. America

733.66	*Vitreisporites pallidus*	$J1_3$	Campanian	183	70	Pocock, 1970a,b; A.R. Sweet, pers. comm., 2004	Alberta
740	*Callistopollenites* sp.	Maastrichtian	Mastrichtian	71	65	Jansonius & Hills, 1977; A.R. Sweet, pers. comm., 2004	Alberta
743.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2004	NWT
743.66	*Triatriopollenites granilabratus*	CHE1	CHE lower 4b	60	40	Parsons, 2000	NWT
743.66	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
770	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
780	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
783.66	*Kuylisporites lunaris*	Early Cretaceous	?Early Cretaceous	146	100	Singh, 1971	Alberta
790	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
793.66	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
800	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
803.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2005	NWT
803.66	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
803.66	*Paraalnipollenites alterniporus*	Paleocene	Late Eocene, ?Oligocene	65	34	Rouse, 1977; Ioannides & McIntyre, 1980; Long & Sweet, 1994; Parsons, 2000; Palynodata Inc. & White, 2008	Eurasia & N. America, N of 20°
813.66	*Pistillipollenites macgregorii*	Chron 26n	Late Eocene	60	34	11-ARS-1998; White, 2009	Ellesmere Island, Beaufort-Mackenzie region
813.66	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
823.66	Tricolpate type H of Parsons 2000	mid CHE3	CHE4c	44	28	Parsons, 2000	NWT
823.66	*Triatriopollenites granilabratus*	CHE1	CHE lower 4b	60	40	Parsons, 2001	NWT
823.66	*Singularia* sp.	Late Campanian	Maastrichtian	74	65	A.R. Sweet, pers. comm. 12004	Alberta
823.66	*Hazaria sheopiariae*	Campanian	Paleocene	84	55	Srivastava 1971; A.R. Sweet, pers. comm., 2004	Alberta
830	*Triatriopollenites granilabratus*	CHE1	CHE lower 4b	60	40	Parsons, 2000	NWT
833.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2000	NWT
840	Triporate type D of Parsons 2000	upper CHE2	CHE4b	56	34	Parsons, 2000	
840	*Triatriopollenites granilabratus*	CHE1	CHE lower 4b	60	40	Parsons, 2000	NWT
840	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
843.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2000	NWT
843.66	*Paraalnipollenites alterniporus*	Paleocene	Late Eocene, ?Oligocene	65	34	Rouse, 1977; Ioannides & McIntyre, 1980; Long & Sweet, 1994; Parsons, 2000; Palynodata Inc. & White, 2008	Eurasia & N. America, N of 20°
843.66	*Hazaria sheopiariae*	Campanian	Paleocene	84	55	Srivastava 1971; A.R. Sweet, pers. comm., 2004	Alberta
843.66	*Azonia* sp.	?Coniacian	Late Maastrichtian	89	65	Nichols & Sweet, 1995	western interior N.

							America
853.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2000	NWT
853.66	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
853.66	*Azonia cribrata*	Assemblage 6, late Campanian	Assemblage 6, late Campanian	78	70	Nichols & Sweet, 1994	Bonnet Plume & Brackett basins
853.66	*Hazaria sheopiariae*	Campanian	Paleocene	84	55	Srivastava 1971; A.R. Sweet, pers. comm., 2004	Alberta
860	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2000	NWT
860	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
863.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2000	NWT
863.66	*Pistillipollenites macgregorii*	Chron 26n	Late Eocene	60	34	11-ARS-1998; White, in press	Ellesmere Island, Beaufort-Mackenzie region
863.66	*Triatriopollenites granilabratus*	CHE1	CHE lower 4b	60	40	Parsons, 2004	NWT
863.66	*Hazaria sheopiariae*	Campanian	Paleocene	84	55	Srivastava 1971; A.R. Sweet, pers. comm., 2004	Alberta
873.66	*Paraalnipollenites alterniporus*	Paleocene	Late Eocene, ?Oligocene	65	34	Rouse, 1977; Ioannides & McIntyre, 1980; Long & Sweet, 1994; Parsons, 2000; Palynodata Inc. & White, 2008	Eurasia & N. America, N of 20°
873.66	*Azonia cribrata*	Assemblage 6, late Campanian	Assemblage 6, late Campanian	78	70	Nichols & Sweet, 1995	Bonnet Plume & Brackett basins
890	*Momipites wyomingensis*	P2	Eocene	63	34	Nichols & Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
893.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2000	NWT
893.66	*Triatriopollenites granilabratus*	CHE1	CHE lower 4b	60	40	Parsons, 2000	NWT
893.66	*Hazaria sheopiariae*	Campanian	Paleocene	84	55	Srivastava 1971; A.R. Sweet, pers. comm., 2004	Alberta
893.66	*Aquilapollenites* sp.	?Coniacian-Santonia	Late Maastrichtian	86	65	Nichols & Sweet, 1993	Yukon & Northwest Territories
898.66	*Triatriopollenites pulcher*	CHE3	CHE4c	48	28	Parsons, 2000	NWT
898.66	*Triatriopollenites granilabratus*	CHE1	CHE lower 4b	60	40	Parsons, 2000	NWT

Table 7. Taxa having a LAD within 200 ft (61 m) above and below the Kugmallit - Mackenzie Bay formation boundary in Nuktak C-22 (Norris, 1986) and Adgo F-28 (Norris, 1997; McNeil, in White, 2009). Taxa are spelled and are listed in the same order as in the source stratigraphic range charts. The dark line represents the formational boundary. The taxa in bold font are taxa in common or very similar between the two wells.

Feet from	Nuktak C-22	Adgo F-28
100-200 ft above	***Intratriporopollenites crassipites*** *Cupuliferoipollenites oviformis* *Dicellaesporites popovii* *Ostryoipollenites* sp. cf. *O. rhenanus* *Sparganiaceaepollenites neogenicus*	*Echinatisporis* sp. A Norris
0-100 ft above Mack. Bay Fm.	*Annutriporites tripollenites* ***Dyadosporites oblongatus*** *Biretisporites potoniaei* Del. & Spr. **Fungal hyphae type G** *Staphlosporonites delumbus* *Baculatisporites quintus*	*Hypoxylonites pirozynskioides* Eslik *Juglanspollenites verus* Raatz **Fungal hyphae type G Norris** *Multicellaesporites compactilis* Ke et Shi ex Sung et al. ***Dyadosporites*** sp. A Norris *Ericipites antecursoroides* Norris *Piceaepollenites* sp. A Norris *Sequoiapollenites polyformosus* Thiergart
Kugmallit Fm. 0-100 ft below		*Momipites wyomingensis* Nichols and Ott *Caryapollenites inelegans* Nichols and Ott *Aceripollenites tener* (Samoilovitch) Norris *Multicellaesporites margaritus* Ke et Shi ex Sung et al. *Monoporisporites* sp. cf. *M. cupoliformis* Sheffy and Dilcher *Montanapollis globosiporus* (Samoilovich) Srivastava *Integricorpus* sp. A Norris *Verrucatosporites favus* (Potonie) Thompson and Pflug

		Retitriletes cf. *R. novomexicanus* (Anderson) Norris *Intratriporopollenites minimus* Mai *Cupuliferoidaepollenites pusillus* (Potonie) Potonie *Tricolpites hians* Stanley
100-200 ft below	*Pinuspollenites labdacus* *Tricolpites hians* Stanley *Reduviasporonites anangus* *Quercoidites microhenrica* *Ulmoideipites tricostatus* *Reduviasporonites* sp. A *Striacolporites* sp. A	*Momipites waltmanensis* Nichols and Ott *Pluricellaesporites* cf. *conspicuus* (Ke et Shi) Norris *Caryapollenites veripites* (Wilson and Webster) Nichols and Ott

Table 8. Estimated minimum January and July paleotemperature estimates based on modern North American relatives of fossil pollen (Thompson, 1999a,b; 2001).

Mallik 5L-38 depth interval (m)	**Fossil pollen type**	**Modern American relatives (Thompson et al., 1999, 2001)**	**January min. mean monthly temp. (° C)**	**July min. mean monthly temp. (° C)**
933.65 - 940.95 m	*Carya*	*Carya cordiformis*	-17	17
		Carya ovata	-13	17
	Nyssa	*Nyssa sylvatica*	-12	15
	Quercus	*Quercus* East	-23	13
	Ulmus-type	*Ulmus*	-23	13
		Planera aquatica	0	26
Range of temperature limits			**-17 to -23**	**13 to 26**
1005.18 -1005.56 m	*Carya*	*Carya cordiformis*	-17	17

		Carya ovata	-13	17
	Ilex-type	*Nemopanthus collinus*	-4	17
		Ilex verticillata	-17	14
	Juglans	*Juglans* East	-15	15
	Liquidambar	*Liquidambar styraciflua*	-4	15
	Nyssa	*Nyssa sylvatica*	-12	15
	Quercus	*Quercus* East	-23	13
	Ulmus-type	*Ulmus*	-23	13
Range of temperature limits			**-4 to -23**	**13 to 17**
1043.16 -1053.68 m	*Erdtmanipollis procumbentiformis*	*Pachysandra procumbens* (by range of *Liriodendron tulipifera*)	-10	17
Range of temperature limits			**-10**	**17**
1081.87-1081.90 m	*Magnolia*-type	*Magnolia acuminata*	-7	18
		Magnolia virginiana	-3	22
		Magnolia tripetala	-5	18
Range of temperature limits			**-3 to -7**	**18 to 22**

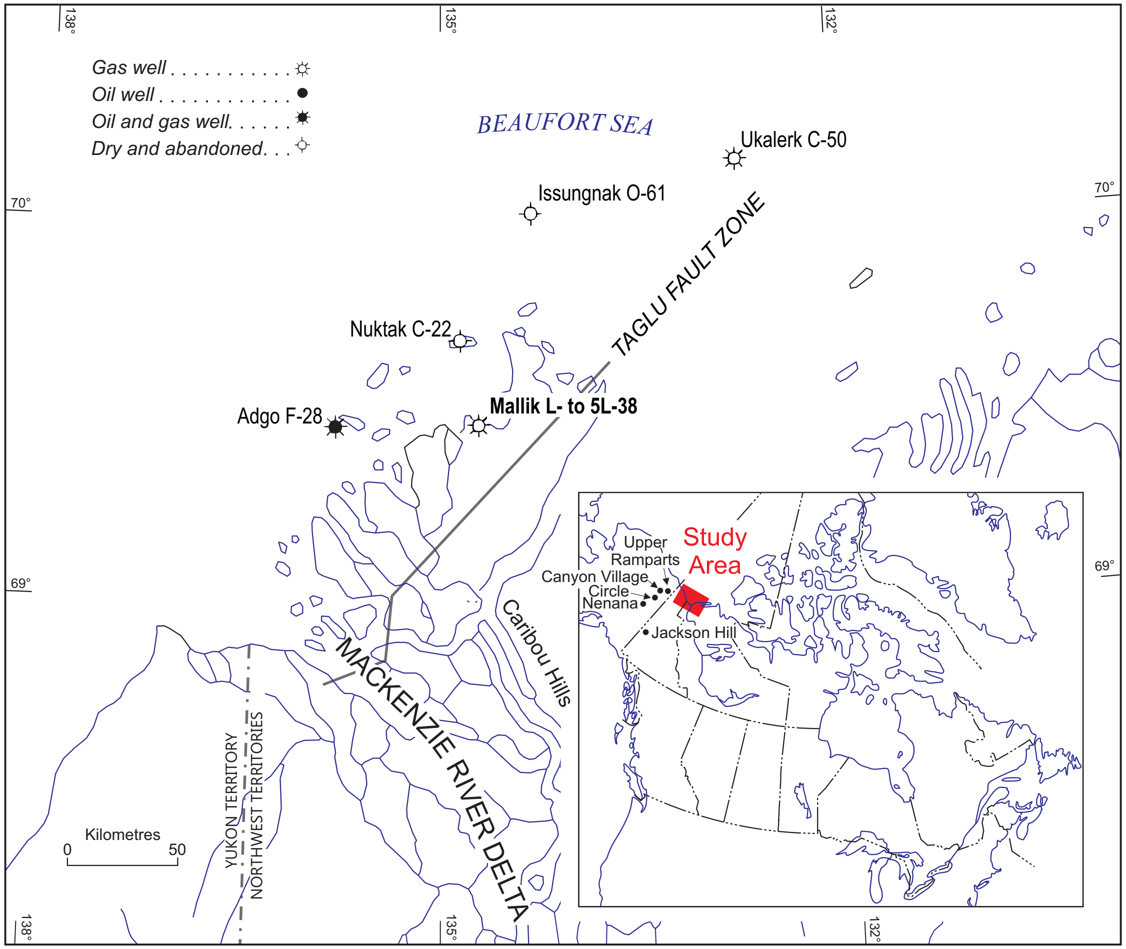

Figure 1. Location of wells and sections.

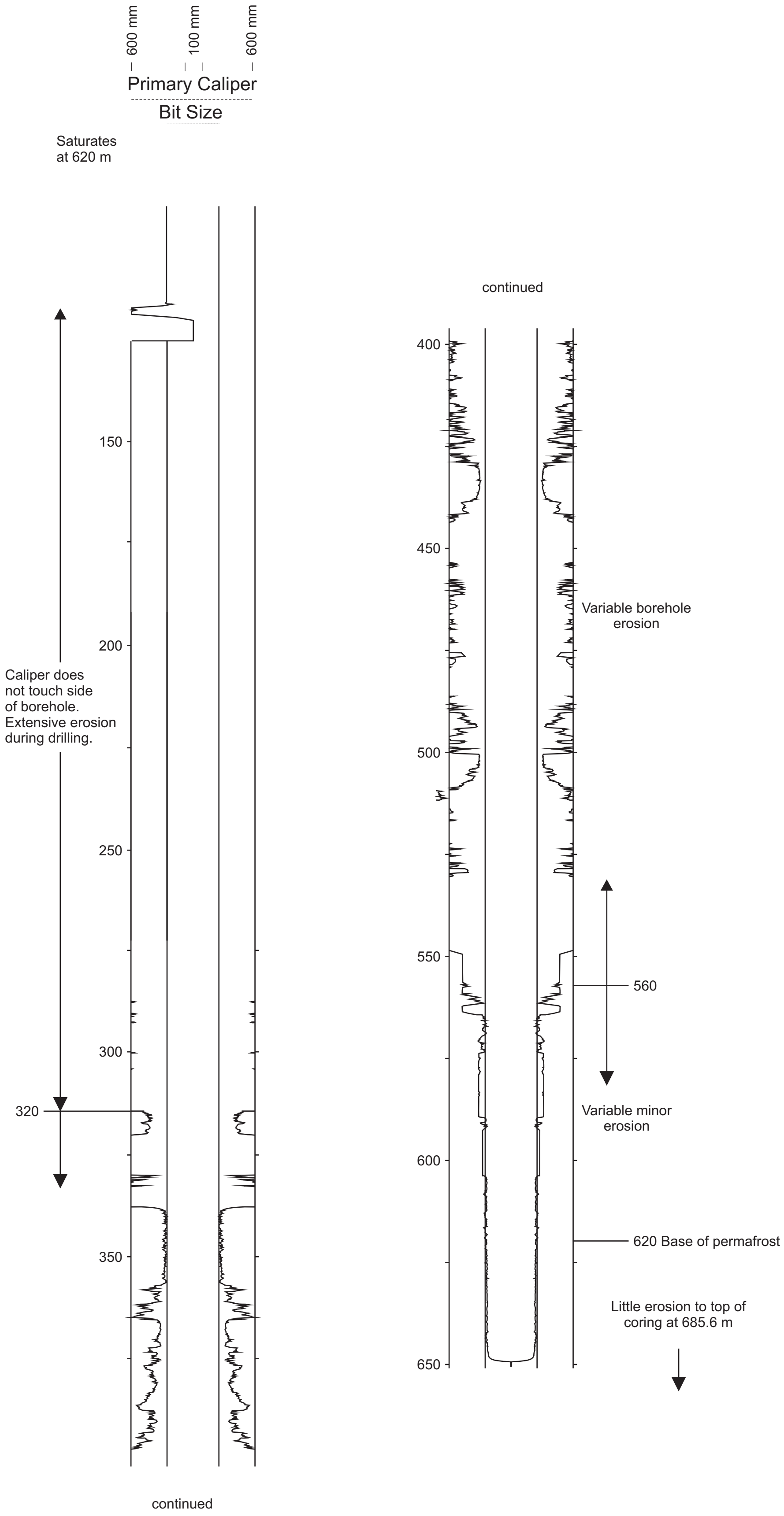

Figure 2. Mallik 5L-38 caliper log.

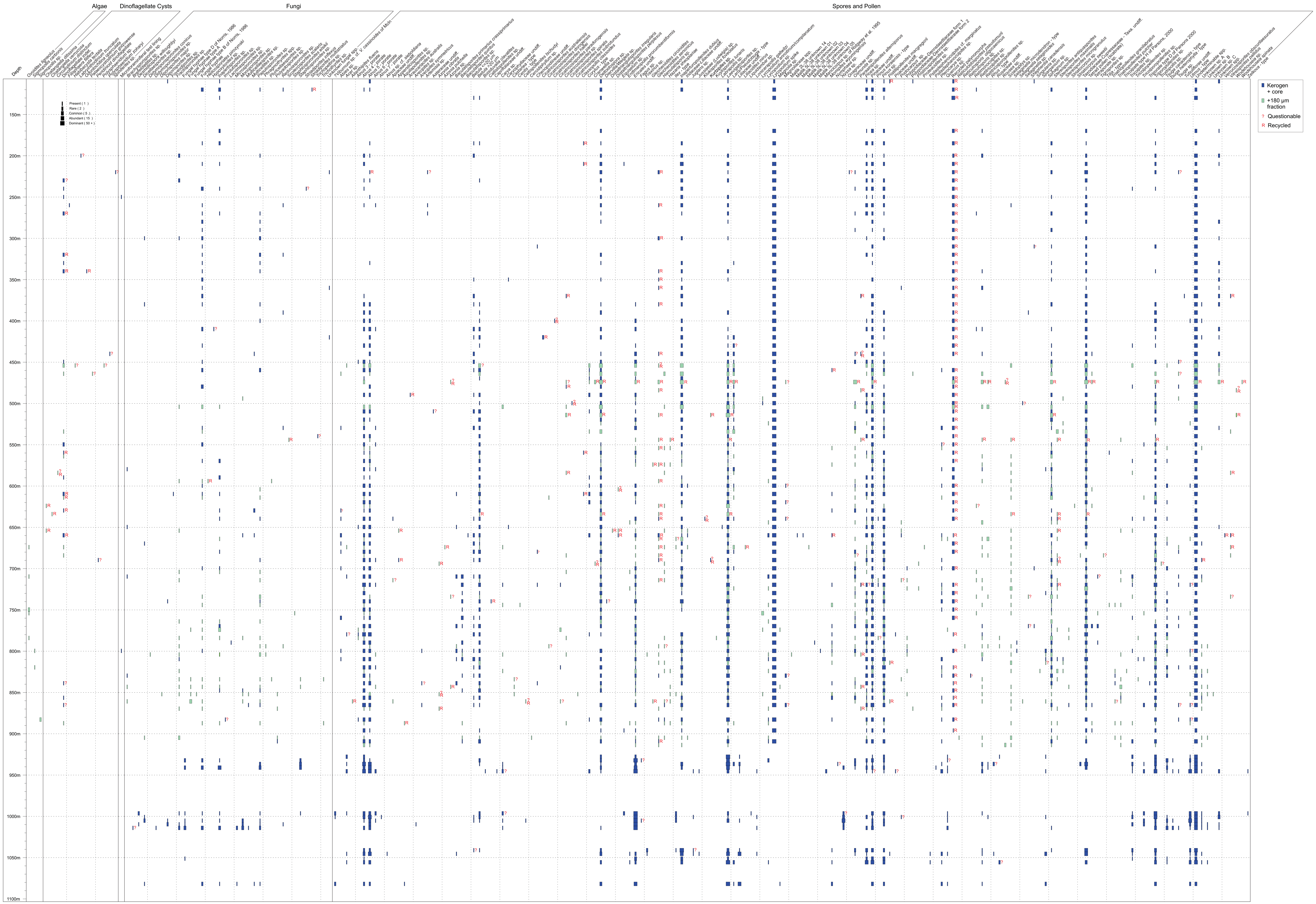

Figure 3. Mallik 5L-38 palynomorphs recorded in kerogen and +180 µm fractions from cutting samples of 105 to 900 m depth, and from coal core samples from 940 to 1082 m depth. Palynomorphs are plotted alphabetically and by relative abundance and by group. Blue represents the kerogen fraction and coal core samples (Analyst JMW). Green represents oxidized preparations of the + 180 µm fraction from 450 m to 900 m (analyst Fract), that are plotted 3.66 m below their true depth. This relative abundance plot presents the occurrences of taxa along with the qualifiers, “?”, to denote questioned identifications.

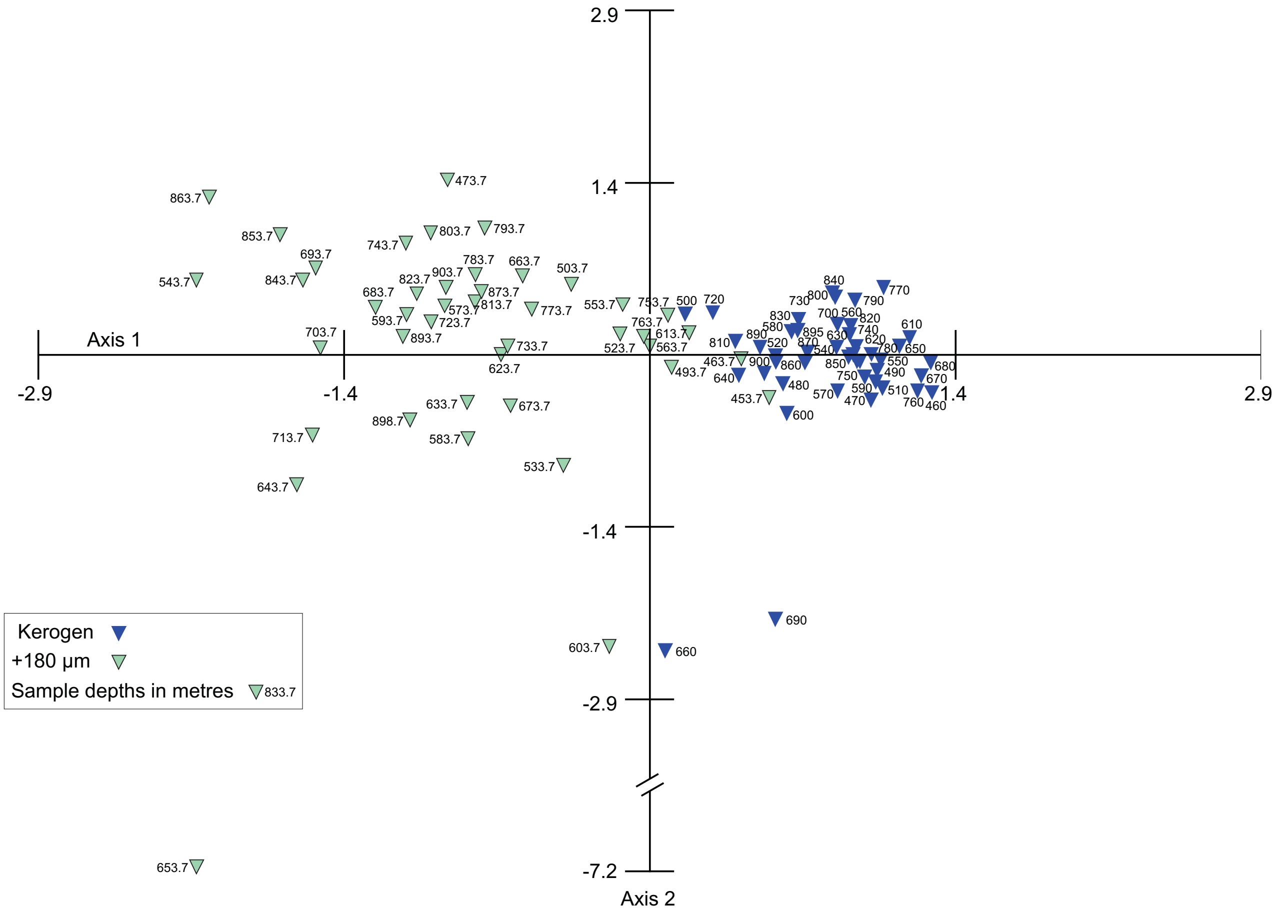

Figure 4. Axes 1 and 2 from correspondence analysis results of Mallik 5L-38 pollen and filicale spore taxa, samples from 450 to 900 m with paired kerogen +180 µm analyses that are designated as 3.66 m below their true depth. Samples 483.66 m and 513.66 m are omitted, as are taxa with only one occurrence.)

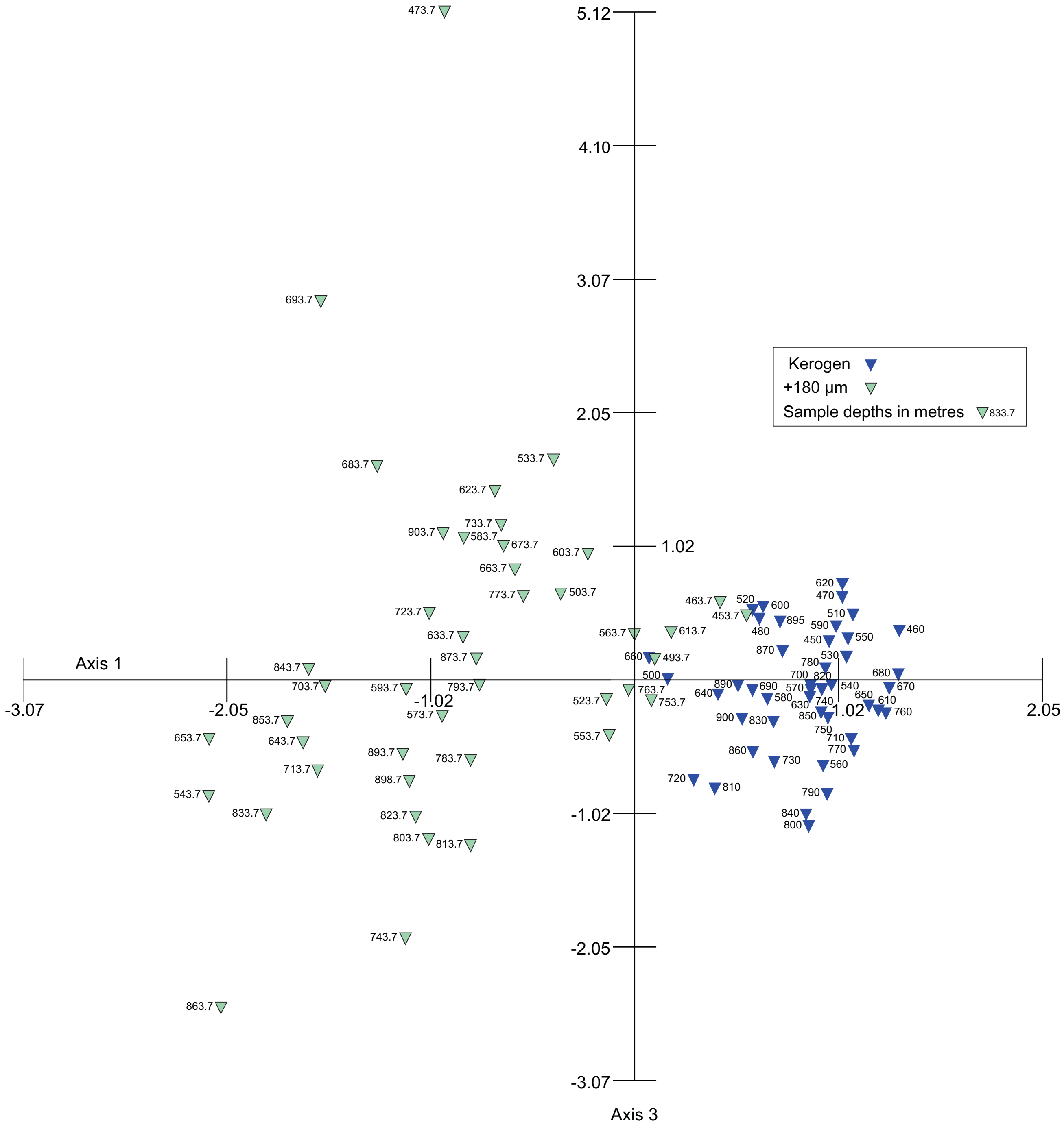

Figure 5. Axes 1 and 3 from correspondence analysis results of Mallik 5L-38 pollen and filicale spore taxa, samples from 450 to 900 m with paired kerogen +180 µm analyses that are designated as 3.66 m below their true depth. Samples 483.66 m and 513.66 m are omitted, as are taxa with only one occurrence. The dispersion of the data on Axis 3 allows the sample distribution on Axis 1 to be seen with less overprinting of data points and labels.

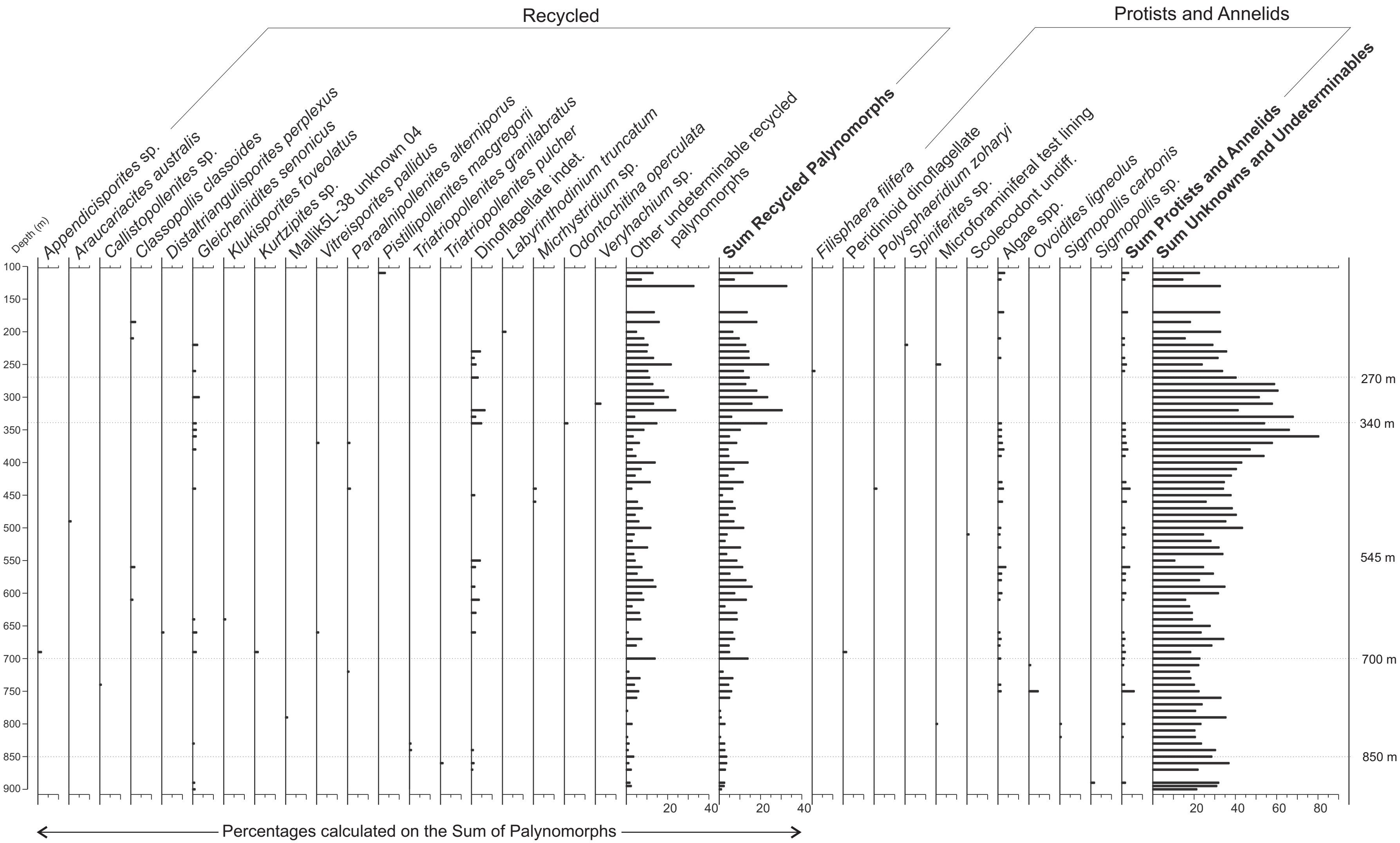

Figure 6. Recycled taxa, protists and unknown and undeterminable palynomorphs in the cutting kerogen fraction, 105 to 900 m.

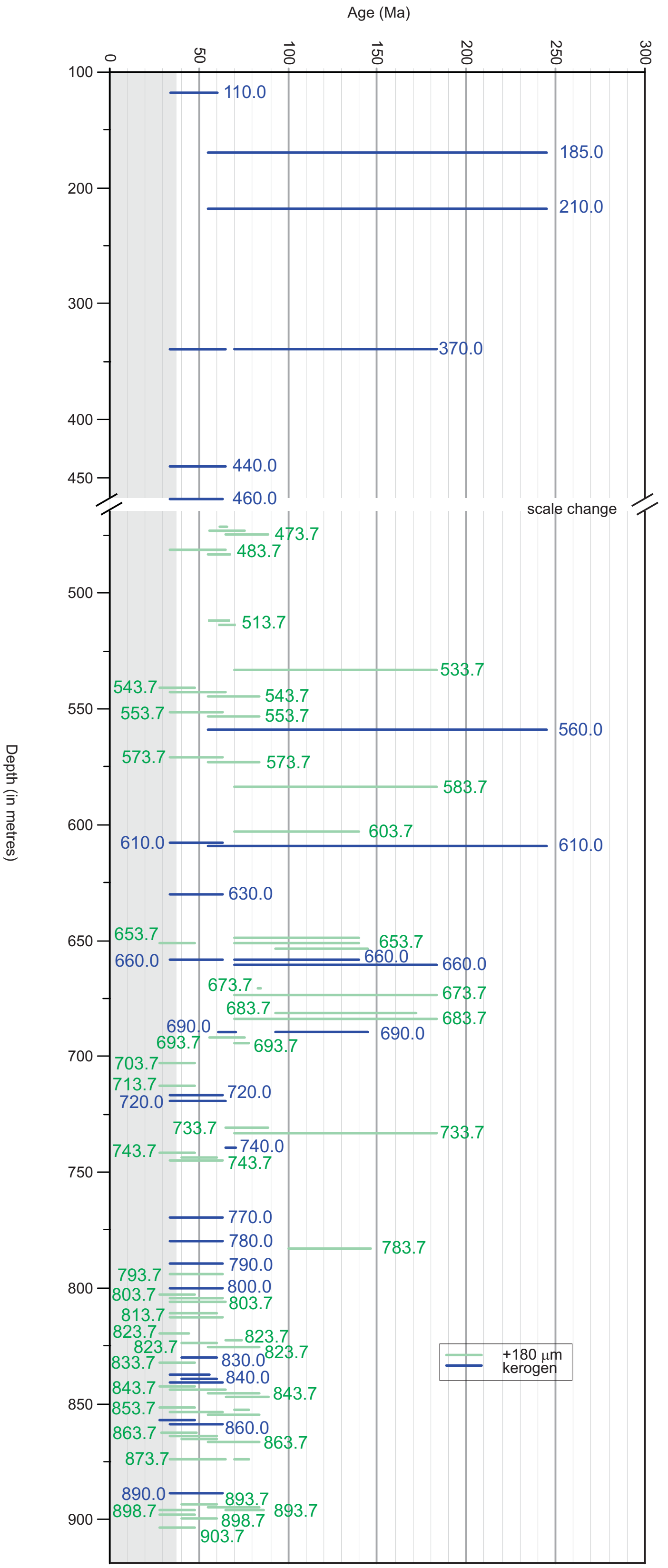

Figure 7. The age ranges of selected taxa which are considered to be likely recycled, for which one can provide reasonably certain age constraints, and their occurrence in the cuttings samples, 105 to 900 m. More than one taxon may be plotted per sample. Samples in green are the +180 µm fraction, and samples in blue are the kerogen fraction. A toned band indicates the estimated age range of the sediment being analysed. The ages cited emphasize stratigraphic ranges in northern North American palynostratigraphy using the ICS time chart (Gradstein et al., 2004).

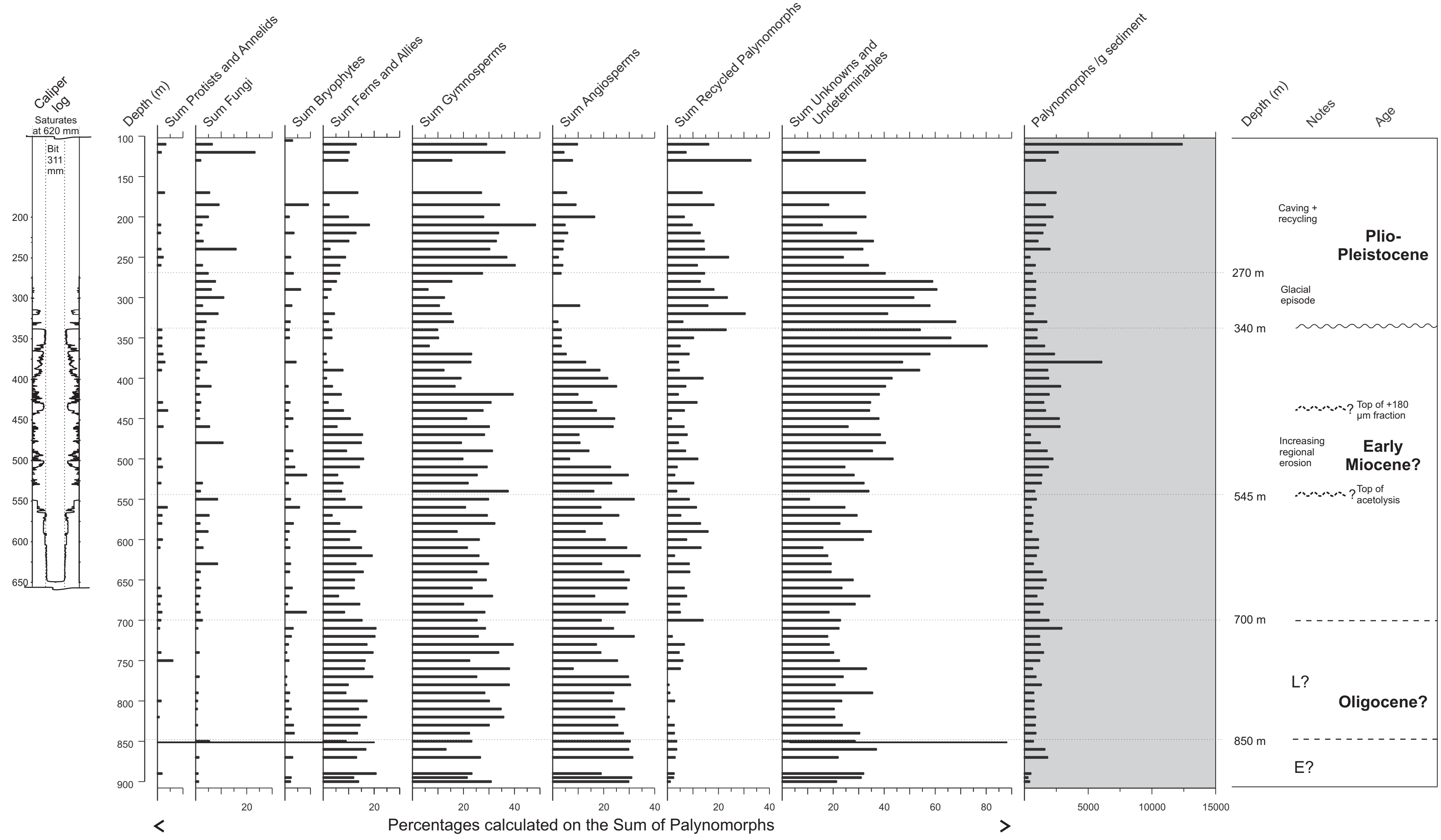

Figure 8. Percentages of groups of palynomorphs in cutting kerogen samples, calculated on the Sum of Palynomorphs, and concentration / gram of sediment, 105 to 900 m.

Figure 9. Percentages of terrestrial palynomorphs recorded in cutting kerogen samples, 105 to 900 m. Percentages are calculated on the Sum of Terrestrial Palynomorphs.

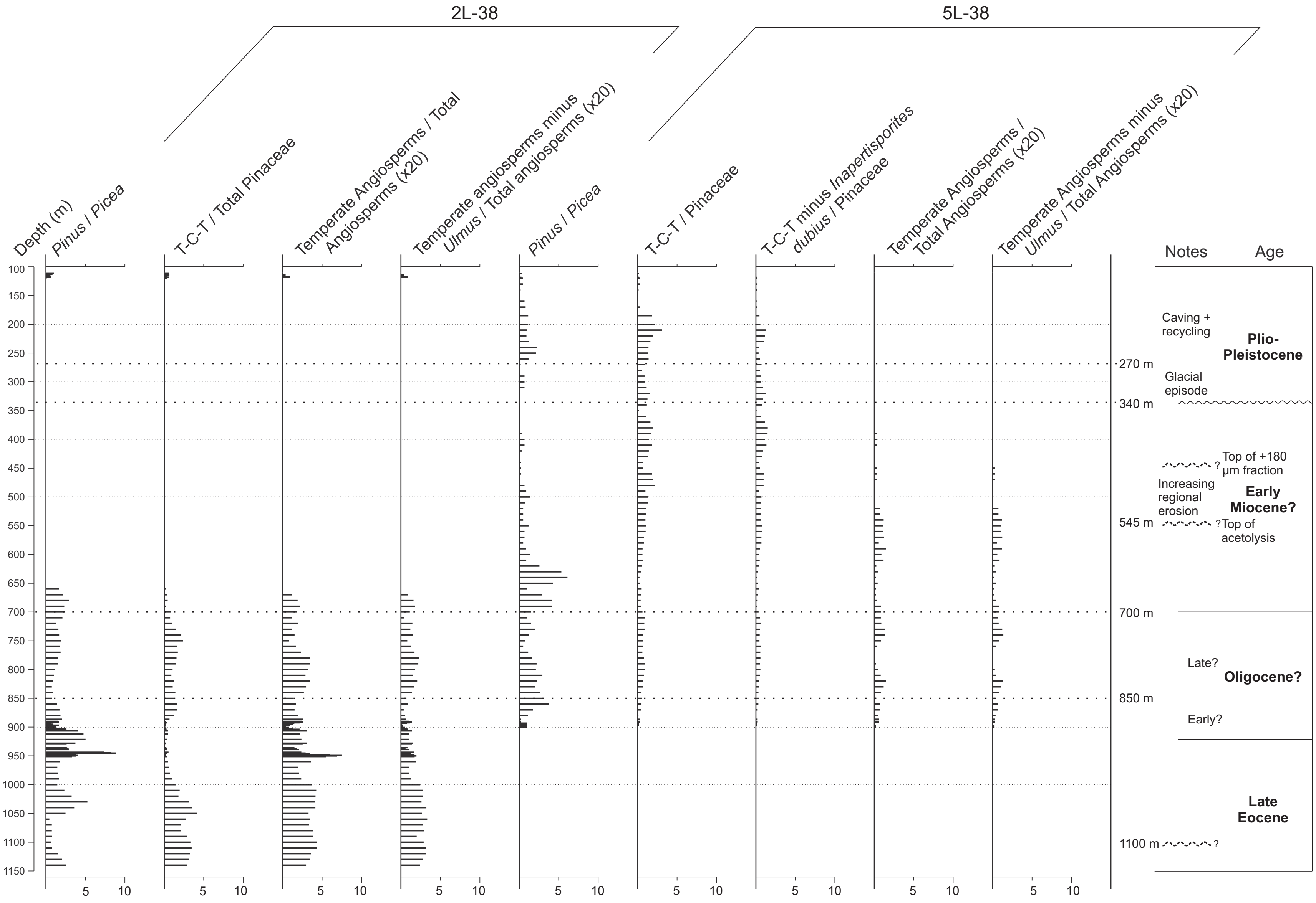

Figure 10. Ratios of selected pollen taxa in Mallik 2L-38 and 5L-38 wells. The ratios for 5L-38 are calculated following the parameters explained in White (2009) and have been smoothed with a three point moving average. The two wells have been interfiled by depth of sample. Between 870 and 900 m, the wells have samples at different intervals. Where the one of the wells has a sample and data, and the other has no data, zero values are entered to force consistent scaling. This has greatest effect on the moving average values of 5L-38 by reducing the values, at 870, 890, 895 and 900 m. This does not fundamentally affect the interpretation. Values of Temperate angiosperms/Total angiosperms, and Temperate angiosperms minus Ulmus/ Total angiosperms are multiplied x20 for visibility.

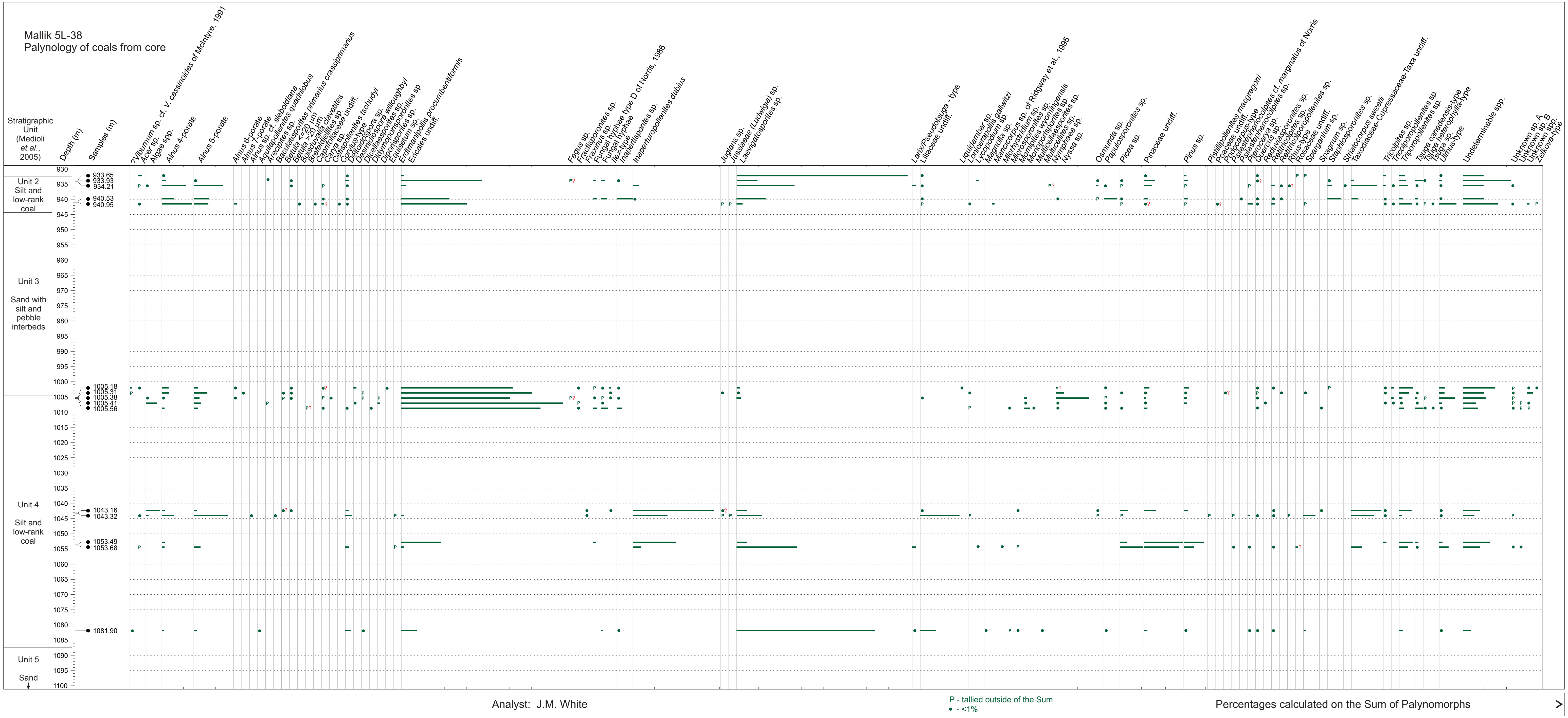

Figure 11. Percentage plot of palynomorphs from coal samples from core, 933.65 to 1081.90 m in Mallik 5L-38. Percentages are calculated on the count sum of palynomorphs.

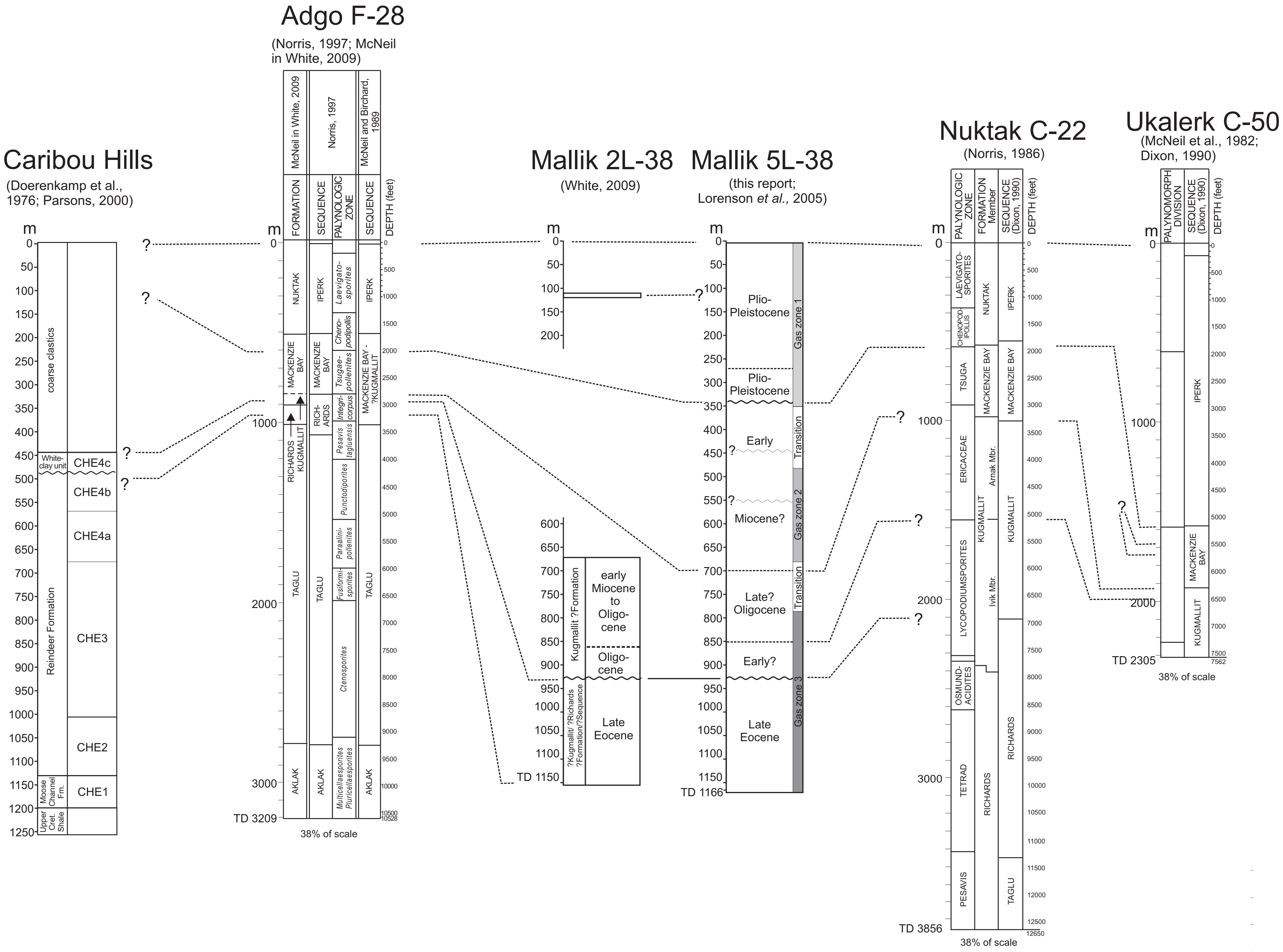

Figure 12. Palynological correlation of Late Eocene and younger strata in Mallik 5L-38 and 2L-38 wells to Beaufort-Mackenzie Basin wells and sections discussed in the text. For correlation of older strata, see the references indicated.