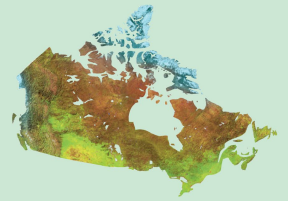


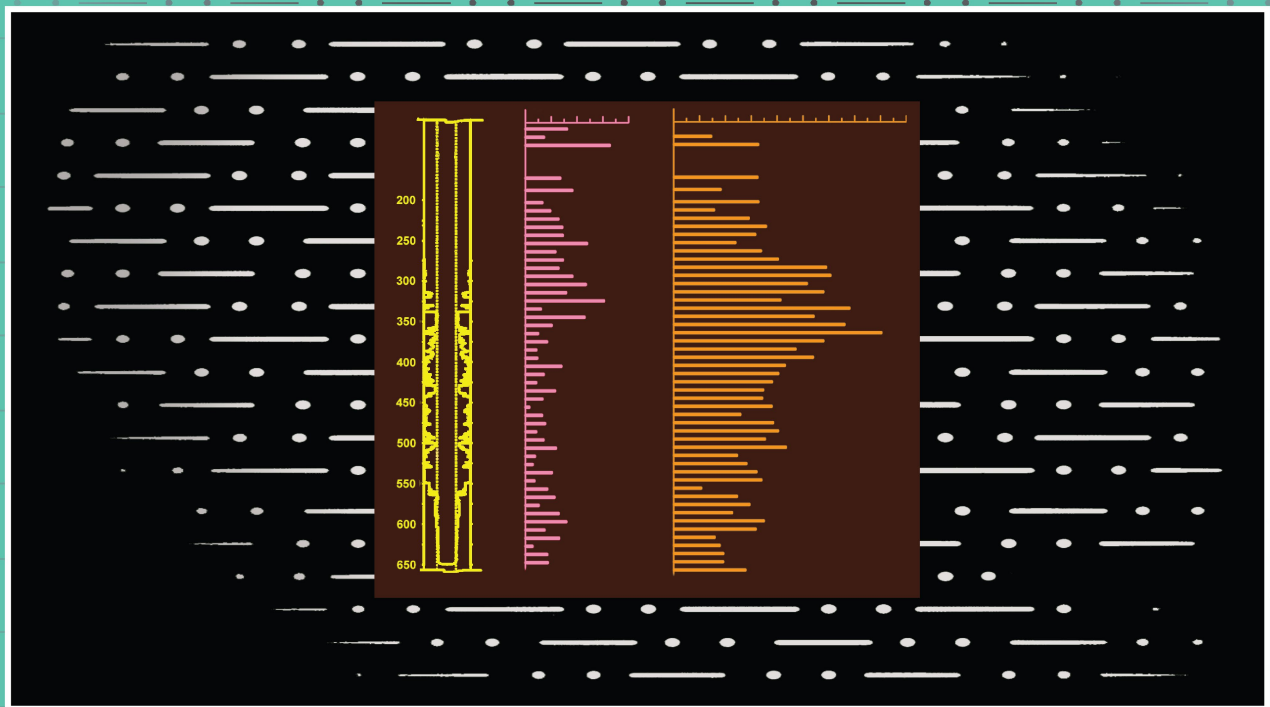


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**The palynostratigraphy, age, and environment of strata
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the recycled and contemporaneous palynomorphs**

J.M. White

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Cover illustration

Graphic representation of data relevant to the interpretability of the palynological record in mid- to upper Cenozoic strata in the Mallik 5L-38 well, Beaufort-Mackenzie Basin. The yellow caliper log for the upper 650 m shows that the well bore is eroded beyond the reach of the calipers in the upper 300 m, but the bore is at gauge at 650 m. Light red shows the percentage of identifiable, recycled palynomorphs, increasing significantly in the Pliocene-Pleistocene section above 340 m. Orange shows the percentage of palynomorphs too corroded for identification and the curve is likely a combination of both landscape erosion and some well casing. The well yields an increasingly interpretable record when more competent rocks are penetrated.

Critical review

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The palynostratigraphy, age, and environment of strata penetrated by the Mallik 5L-38 gas-hydrate research well, Northwest Territories, determined by differentiating the recycled and contemporaneous palynomorphs

Abstract

Quantitative palynostratigraphy of the Mallik 5L-38 well provides insight into palynomorph recycling and a Late Eocene age for the basal coals. Samples from 450 m to 900 m yielded a fraction on the 180 μm screen having a high concentration of recycled palynomorphs, releasable by standard oxidation. The fraction that passed through the screen was not oxidized and yielded more in-place palynomorphs. This observation may affect interpretation of other regional upper Cenozoic studies of oxidized samples. The 0–270 m interval is interpreted to be late Pliocene to Pleistocene. The regional erosional unconformity below the Iperk Sequence is identified at 340 m, with other possible unconformities at 445 m and 550 m. The interval from 340 m to 700 m is thought to be Early Miocene. The 700–900 m interval is tentatively identified as Oligocene. Climate proxy ratios, compared with those of Mallik 2L-38 well between 670 m and 900 m are inconsistent, possibly due to low palynomorph counts or a change from a coherent Late Eocene record to a noisy Oligocene and younger record. An erosional unconformity near 930 m may have resulted from sea-level decline due to earliest Oligocene glaciation in Antarctica. Core samples from coal beds between 933.65 m and 1081.90 m yielded Late Eocene palynomorphs unlikely to be recycled, and some pollen associated with earlier Eocene ages. The coal swamps seem to be an environment where relict species can persist. A warm paleoclimate is indicated, consistent with an Eocene age.

Résumé

La palynostratigraphie quantitative du puits Mallik 5L-38 indique qu'il y aurait eu un remaniement des palynomorphes et que les charbons à la base du puits dateraient de l'Éocène tardif. Des échantillons prélevés à des profondeurs de 450 à 900 m ont donné dans le tamis à maille de 180 μm une fraction renfermant une concentration élevée de palynomorphes remaniés, qui peuvent être libérés par oxydation classique. La fraction qui a passé par les mailles du tamis n'était pas oxydée et révélait davantage de palynomorphes en place. Cette observation peut avoir une incidence sur l'interprétation d'autres études régionales du Cénozoïque supérieur effectuées à partir d'échantillons oxydés. Selon notre interprétation, l'intervalle de 0 à 270 m daterait du Pliocène tardif au Pléistocène. La discordance d'érosion régionale marquant la base de la Séquence d'Iperk est observée à 340 m, alors que d'autres discordances pourraient également se trouver à 445 m et à 550 m. Nous pensons que l'âge de l'intervalle de 340 à 700 m remonterait au Miocène précoce. L'âge de l'intervalle de 700 à 900 m est provisoirement attribué à l'Oligocène. Les rapports servant d'indicateurs indirects du climat sont incompatibles avec ceux de l'intervalle de 670 à 900 m du puits Mallik 2L-38, peut-être en raison de la faible quantité de palynomorphes ou du passage d'une suite fossilifère cohérente à l'Éocène tardif à une parasitée à l'Oligocène et aux temps plus récents. La discordance d'érosion située près de 930 m peut être le résultat d'une baisse du niveau de la mer causée par la glaciation de l'Oligocène initial dans l'Antarctique. Les carottes prélevées dans des lits de charbon situés entre 933,65 et 1081,90 m ont livré des palynomorphes de l'Éocène tardif, probablement non remaniés, ainsi que de pollen associé à des âges éocènes plus anciens. Les marais houillers semblent constituer un environnement où des espèces reliques peuvent persister. Tout semble indiquer un paléoclimat chaud, ce qui serait conforme aux conditions prévalant à l'Éocène.

SUMMARY

The purpose of this study is to refine the geological understanding of the rocks in the Beaufort-Mackenzie Basin, and so contribute to understanding the stratigraphy, paleoenvironment, paleoclimate, and timing of hydrocarbon generation in the region. The data and interpretation herein are an analysis of the pollen and spores found in rock samples from the Mallik 5L-38 gas hydrate research well in the Mackenzie River delta, filling gaps and complementing the analysis of the adjacent Mallik 2L-38 well. Both wells yielded better quality samples of rock than is available from industrial wells because they were drilled with chilled mud to reduce well-bore caving, cores were cut, and they had close sample intervals for drill-bit cuttings.

The first hurdle in the analysis of the Mallik 5L-38 well is to provide insight into the problem of recycling of fossils, a process whereby fossil pollen and spores are eroded from older rocks and redeposited into younger sediments, thereby confusing age interpretation — a vexing problem in studies of regional sediments deposited during the last 34 million years. It is observed here that, during the processing of samples from the 450 m to 900 m interval, the 180 µm mesh screen retains organic matter that contains an assemblage dominated by recycled palynomorphs; these can be released by oxidation. Any sample prepared by oxidation where this fraction is not separated will have a high concentration of recycled palynomorphs. Oxidation has been a standard palynology preparation technique for Beaufort-Mackenzie Basin wells, so this may affect some previous results, although the stratigraphic interval over which this problem applies has not been well constrained by this study. Samples in this study that were not oxidized still have a significant component of recycled palynomorphs, but yield sufficient palynomorphs that likely are not recycled to provide a useful interpretation.

The Mallik 5L-38 well, 0–270 m interval is interpreted to be late Pliocene to Pleistocene and contains abundant recycled fossils. Likewise, the interval from 270 m to 340 m is dominated by the deposition of eroded material. Abundant recycling may represent erosion due to a mid- to late Pliocene or Pleistocene glacial event. In the Pliocene-Pleistocene strata, where the sediment is poorly lithified, the percentage of recycled taxa increases where well-bore diameter is much larger than the bit diameter, which is useful information for future studies. Palynomorph recycling also suggests the acceleration of regional erosion, probably in the Early Miocene.

The regional erosional unconformity below Iperk Sequence is identified at 340 m, with other possible unconformities at 445 m and 550 m. In the interval

SOMMAIRE

L'objectif de la présente étude consiste à améliorer les connaissances sur la géologie des roches du bassin de Beaufort-Mackenzie, et ainsi aider à comprendre la stratigraphie, le paléoenvironnement, le paléoclimat et la chronologie de la formation des hydrocarbures dans la région. Les données et l'interprétation contenues dans le présent document résultent d'une analyse du pollen et des spores trouvés dans des échantillons de roche provenant du puits de recherche sur les hydrates de gaz Mallik 5L-38, dans le delta du Mackenzie, et permettent de combler des lacunes ainsi que d'offrir un complément à l'analyse du puits adjacent Mallik 2L-38. Les échantillons de roche prélevés dans les deux puits étaient de meilleure qualité que ceux provenant de puits de l'industrie, étant donné qu'ils ont été forés à l'aide de boue refroidie afin de réduire l'éboulement des parois du trou de forage, que des carottes ont été prélevées et que les intervalles d'échantillonnage étaient rapprochés pour les déblais de forage.

La première difficulté dans l'analyse du puits Mallik 5L-38 consiste à traiter du problème de remaniement des fossiles, un processus par lequel le pollen et les spores fossiles sont érodés de roches anciennes et redéposés dans des sédiments plus récents, créant ainsi de la confusion pour l'interprétation de l'âge — un problème épineux pour les études des sédiments déposés dans la région durant les 34 derniers millions d'années. On observe que, pendant le traitement des échantillons provenant de l'intervalle de 450 à 900 m, le tamis à maille de 180 µm retient de la matière organique qui contient un assemblage à prédominance de palynomorphes remaniés; ceux-ci peuvent être libérés par oxydation. Tout échantillon préparé par oxydation, alors que cette fraction n'est pas séparée, aura une concentration élevée de palynomorphes remaniés. L'oxydation a été une technique classique de préparation utilisée en palynologie pour les puits du bassin de Beaufort-Mackenzie, de sorte que des résultats antérieurs peuvent en être affectés, bien que l'intervalle stratigraphique pour lequel ce problème se pose n'ait pas été bien délimité par notre étude. Les échantillons non oxydés prélevés pour l'étude comportent toujours une importante composante de palynomorphes remaniés, mais présentent aussi des palynomorphes vraisemblablement non remaniés en quantité suffisante pour permettre une interprétation utile.

Selon notre interprétation, l'intervalle de 0 à 270 m dans le puits Mallik 5L-38 daterait du Pliocène tardif au Pléistocène et contiendrait des fossiles remaniés en abondance. De même, l'intervalle de 270 à 340 m est caractérisé par le dépôt de matériaux d'érosion. L'important remaniement peut être le résultat d'une érosion causée par un événement glaciaire survenu au Pliocène moyen à tardif ou au Pléistocène. Dans les strates du Pliocène-Pléistocène, où les sédiments sont peu lithifiés, le pourcentage de taxons remaniés augmente là où le diamètre du puits est beaucoup plus grand que celui de l'outil de forage, ce qui représente une information utile pour de futures études. Le remaniement des palynomorphes indique également une accélération de l'érosion à l'échelle régionale, probablement au cours du Miocène précocé.

La discordance d'érosion régionale marquant la base de la Séquence d'Iperk est observée à 340 m, alors que d'autres discordances pourraient également se trouver à 445 m et à 550 m.

from 340 m 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 Early Miocene. Oligocene intervals are tentatively identified from 700 m to 900 m, but palynological definition of the Oligocene is problematic regionally. There are similarities between the pollen zonation and the biogenic and/or thermogenic gas zonation.

Climate proxy ratios of warm-climate taxa are generated to compare with similar analyses in the section of the Mallik 2L-38 well between 670 m and 900 m. Comparisons show that their interpretation is ambiguous, possibly reflecting undersaturated rarefaction curves for the assemblages and low palynomorph counts in samples yielding few palynomorphs. It is also possible that the change from coherent, independent ratio patterns below 886 m in Mallik 2L-38 well to incoherent and out-of-phase patterns in Mallik 2L-38 and Mallik 5L-38 wells may indicate an important stratigraphic change, expressed in palynology as a change from a coherent Late Eocene record to a noisy Oligocene and younger record.

An erosional unconformity about 930 m may have resulted from sea-level decline due to earliest Oligocene glaciation in Antarctica and appears to correlate to an Oligocene unconformity on the Scotian Margin.

Analysis of core samples from coal beds in Mallik 5L-38 well between 933.65 m and 1081.90 m yielded records of palynomorphs that cannot be reasonably attributed to recycling. They confirm that Late Eocene palynomorphs occur in this interval (~37–34 Ma), and show that some palynomorphs usually attributed to older Eocene rocks range into the Late Eocene. The coal swamps seem to be an environment where relict species can persist. 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.

Dans l'intervalle de 340 à 700 m, l'absence d'un assemblage représentant soit le maximum thermique du Miocène moyen, soit le déclin des taxons thermophiles de la période suivante, nous donne à penser que l'intervalle daterait du Miocène précoce. Des intervalles de l'Oligocène sont provisoirement établis entre 700 et 900 m, mais la définition palynologique de l'Oligocène est problématique dans la région. Il existe des similarités entre la zonation pollinique et la zonation de gaz biogène ou thermogène.

Des rapports de taxons de climat chaud servant d'indicateurs indirects du climat sont produits afin de faire une comparaison avec des analyses similaires portant sur l'intervalle de 670 à 900 m dans le puits Mallik 2L38. Des comparaisons montrent que leur interprétation est ambiguë, reflétant peut-être des courbes de rarefaction sous-saturées pour les assemblages et une faible quantité de palynomorphes dans des échantillons qui en donnent peu. Il est également possible que le passage de configurations cohérentes de rapports indépendants en dessous de 886 m dans le puits Mallik 2L-38 à des configurations incohérentes et déphasées dans les puits Mallik 2L-38 et Mallik 5L-38, indique un important changement stratigraphique, exprimé en palynologie par le passage d'une suite fossilifère cohérente à l'Éocène tardif à une suite parasitée à l'Oligocène et aux temps plus récents.

Une discordance d'érosion située à environ 930 m pourrait être le résultat d'une baisse du niveau de la mer causée par une glaciation à l'Oligocène initial dans l'Antarctique. Elle semble être en corrélation avec une discordance de l'Oligocène sur la marge Néo-Écossaise.

L'analyse d'échantillons de carottes prélevées dans des lits de charbon situés entre 933,65 et 1081,90 m dans le puits Mallik 5L-38 ont livré des suites de palynomorphes que l'on ne peut pas attribuer raisonnablement à un remaniement. Ces échantillons confirment que des palynomorphes de l'Éocène tardif se trouvent dans cet intervalle (env. 37-34 Ma) et montrent que certains palynomorphes généralement attribués à des roches plus anciennes de l'Éocène devraient plutôt être classés dans l'Éocène tardif. Les marais houillers semblent être un environnement où des espèces relictives peuvent persister. Un paléoclimat chaud est indiqué par des taxons contemporains de pollen apparentés à ceux d'angiospermes de milieu tempéré qui se trouvent dans le charbon, un paléoclimat qui serait conforme aux conditions prévalant à l'Éocène.

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 Inc., 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, Fig. 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 KB. The base of the conductor hole was 24 m KB (Canadian Petroleum Engineering Inc., 2002). All depth measurements are assumed to be below the KB. Gas-hydrate deposits occur between 892 m and 1107 m (Dallimore and Collett, 2005b).

White (1999, 2009; J. White, oral presentation, Whistler Gas Hydrate Conference, 22–24 January, 2003, Whistler, British Columbia) 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 m and 118 m. This analysis of the Mallik 5L-38 well is to provide biostratigraphic and paleoclimatic interpretations for the 0–670 m interval, and to refine the biostratigraphic interpretations made in the Mallik 2L-38 well. This Mallik 5L-38 well analysis and report is based on cutting samples analyzed at 10 m intervals between 100 m and 900 m, and coal samples from 192.6 m of core between depths of 885 m 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 Mallik 5L-38 (Table 1, Fig. 2) give information that bears on the biostratigraphic interpretations. The interpretations from 116 m to 650 m are based on the ‘platform express: cement volume’ log. The amount of hole erosion that took place during drilling is significant

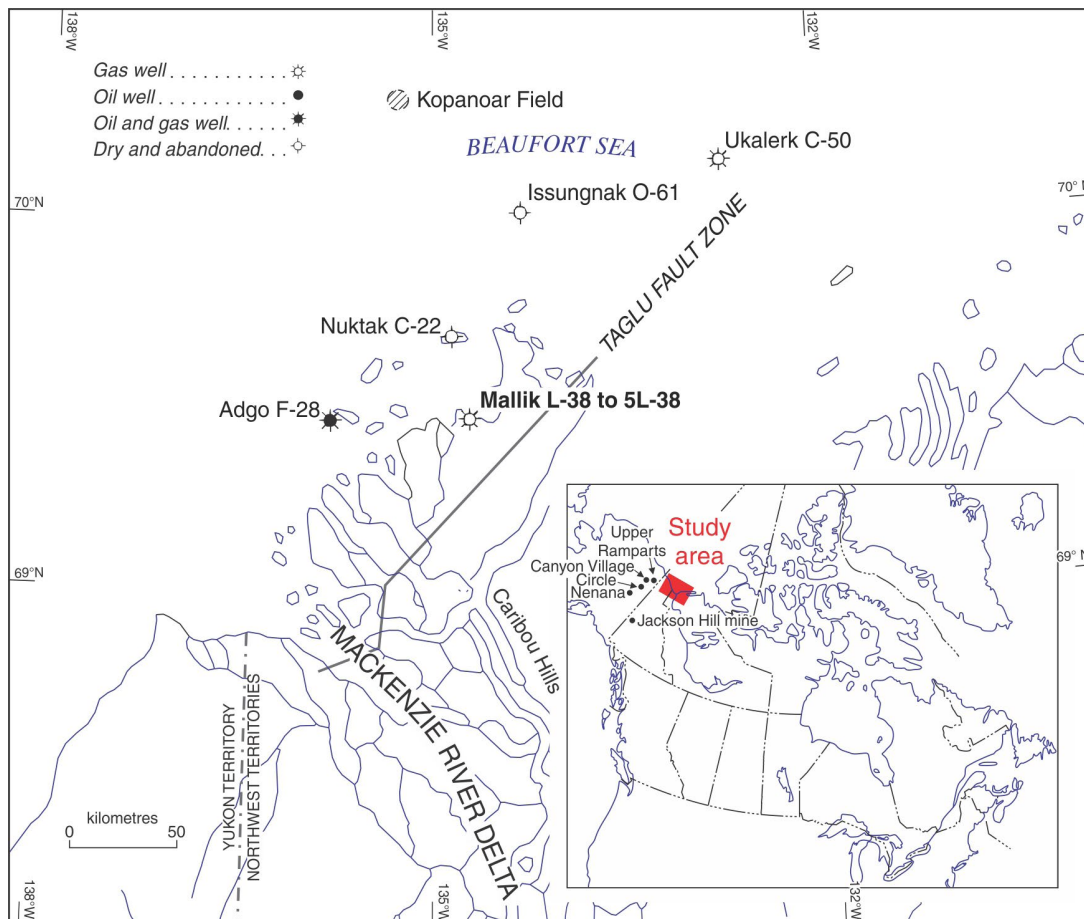


Figure 1. Location of wells and sections.

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 m 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 m and 650 m the hole was eroded,

but much less than above that point, 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 m to 762 m there is little hole erosion, and from 762 m to the top of coring at 885.6 m, there is very little erosion. The base of coring was 1151 m and total depth (TD) was 1166 m.

Table 1. Selected drilling history records of biostratigraphic significance for Mallik 5L-38 well.

Interval				Event	
Interval depth (m) (KB)	Bit size (mm)	Borehole diameter (mm)	Comment on interval	Event depth (m) (KB)	Comment on event
				102	top of <i>Platform express: cement volume log</i>
				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 noneroded sections		
560				560	Change in borehole erosion
				573	Cleaned mud tanks, changed shaker screens
	311	<400	minor erosion, but without major washouts		
				620	Approximatley. base of permafrost; change in erosion probably due to change in permafrost
650				650	Change in logs
				675	Top of <i>Integrated hole/cement volume summary log</i>
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

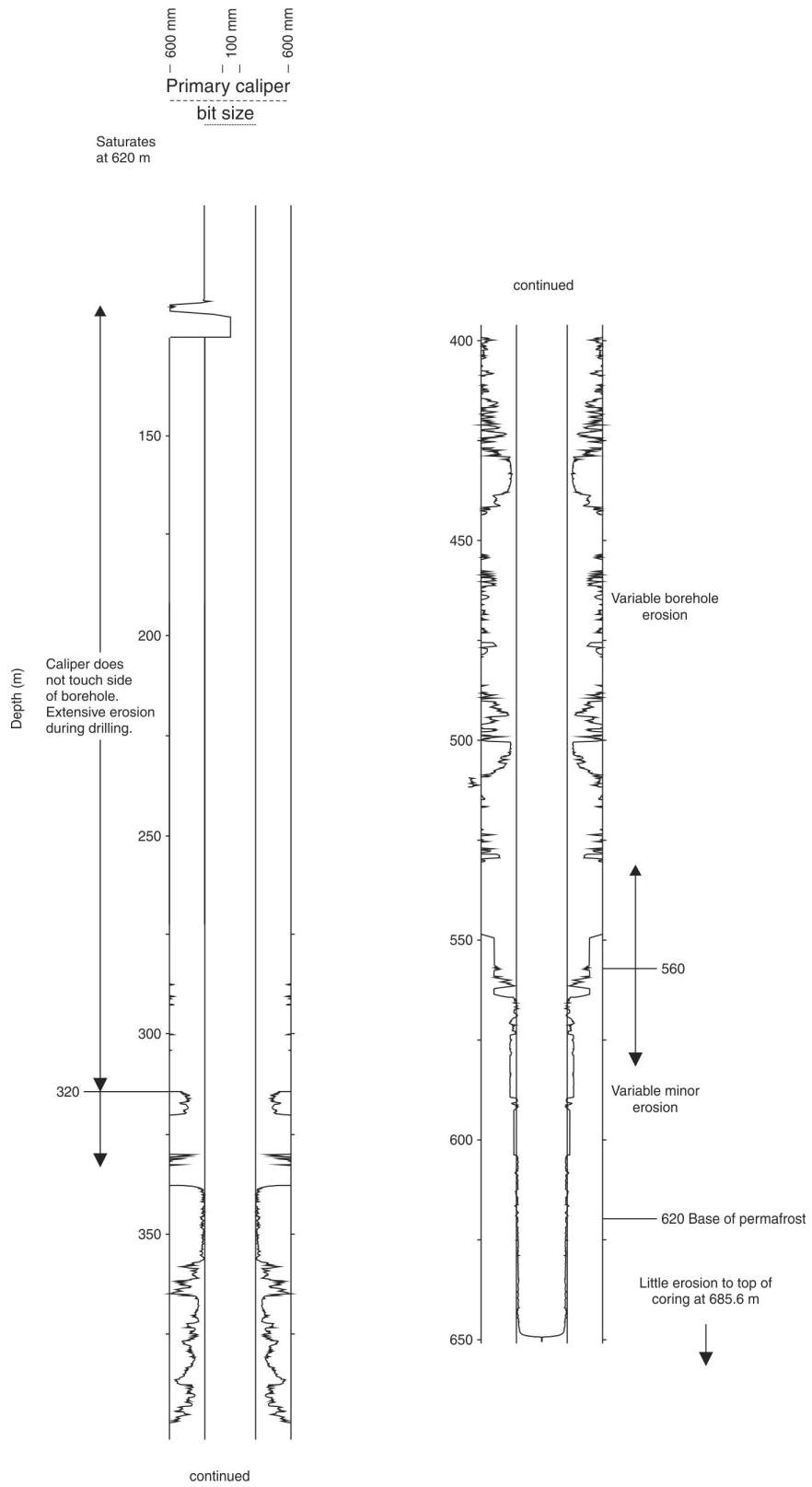


Figure 2. Mallik 5L-38 caliper log, 100–650 m.

Problems and principles guiding this study

This study of Beaufort-Mackenzie Basin palynostratigraphy is guided by the research context, assumptions, and questions discussed below. Given these conditions and assumptions, the following analyses were undertaken, for which the results are presented. Following is the author's 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 or Sequence.
2. Biostratigraphy is optimally done by studying a continuous section that allows inferences based on stratigraphic superposition.
3. During the Eocene, many palynomorphs took on their modern form, so biostratigraphy based on evolutionary and/or 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 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, the modern relatives of which now may be found in China, or in the eastern seaboard of the United States to south-eastern Canada (*see* discussion in White, 2009).
5. Ratios of these categories (above) 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 cannot be compared with previous studies, except with those from Mallik 2L-38 well.
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 $\delta^{18}\text{O}$ 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 tectonic events 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 ka in mid-continental North America, and in aridification in the Tibetan plateau (DeConto and Pollard, 2003; Pälike et al., 2006; Bowen, 2007; Dupont-Nivet et al., 2007; Zanazzi et al., 2007). The Late Oligocene (Chattian Age) warm interval (De Man and Van Simaey, 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 Taxodiaceae-Cupressaceae-Taxaceae pollen occurred as far north as the Upper Ramparts Canyon, northern Alaska (White and Ager, 1994). The palynological signature of the Chattian Age needs further definition (Norris, 1982, 1986).
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 the distributions of which 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 Mallik 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 yielded about 1 km of Cenozoic section, spanning the Late Eocene to the Pliocene-Pleistocene.
9. Palynomorph recycling is a vexing problem in Beaufort-Mackenzie Basin 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 the possibility of range extensions and floristic responses to paleoclimatic events such as warm episodes, or continued survival of species in environmental niches. 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 than the sediment being deposited.
11. Throughout most of the Cenozoic in Arctic Canada, a rich vegetation of gymnosperms and angiosperms existed (Basinger, 1991; Francis, 1991; McIntyre, 1991; Fyles et al., 1994; Matthews and Fyles, 2000; Jahren, 2007). That vegetation should be represented by pollen and spores in sediment. Pollen production must have been substantial and contributed copious amounts of 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 the present state of knowledge, it is only during the mid- to 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 record of pollen and spores was recycling; however, the nonselective sampling of sediment by cuttings skews the record toward inorganic sediment where recycled palynomorphs would be more common.
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 and/or 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 challenge 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-38 and Mallik 5L-38 wells, which were drilled with chilled mud to reduce permafrost melting, and hence caving (from uphole).

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 analyze the palynomorph yield of the sediment samples.

Samples of washed cuttings or core were weighed and two tablets of acetolyzed *Lycopodium* spores (Lund University, Batch 938934) were added per sample to permit measurements of pollen concentration in the preparations (Benninghoff, 1962). Samples of 13 g to 20 g weight were macerated with standard HCl and HF treatment and the residues were screened using 180 μm and 10 μm nominal meshes, removing the fraction 254 μm and larger and 14 μm and smaller (Table 2) (except the interval from 270 m to 345 m, where a 7 μm mesh was used for screening, but was found to make processing too difficult). The 180 μm screen removed 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 made it easier to find palynomorphs. The acid-resistant organic matter had 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

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

Processing / well	Mallik 2L-38		Mallik 5L-38	
	Kerogen	Kerogen fraction	+180 μm fraction	
1. Weigh sample	Yes	Yes	No	
2. Add exotic <i>Lycopodium</i> spike	Yes	Yes	No	
3. HCl	Yes	Yes	No	
4. HF	Yes	Yes	No	
5. Screen, coarse mesh	180 μm (discard any +180 μm fraction)	180 μm (450 m to 900 m)	Residue on screen	
6. Oxidized (5 minutes of hot Schulze solution)	No	No	Yes	
7. Neutralization by ammonium hydroxide	No	No	Yes	
8. Screen, coarse mesh	No	No	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 sodium hypochlorite	Yes	No	No	
11. Neutralization by ammonium hydroxide	Yes	No	No	
12. Acetolysis	No	550 m and below	No	
13. Kerogen slide	Yes	Yes	No	
14. Oxidized slide	No	No	Yes	

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 were macerated by HCl, HF, and five minutes of hot Schulze treatment and screened by hand through 180 μm and 10 μm meshes. Residue from the HCl and HF treatment that was not coaly was acetolyzed and mounted. These 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 of the need for two analyses per sample. This is because, at 450 m and below, L. Dancey, the laboratory technician, observed a considerable amount of organic matter on the 180 μm nominal screen; normally little was observed and was routinely discarded. It was decided that this +180 μm fraction of the sample also needed to be prepared and analyzed, a decision that yielded important insights in this study. That fraction retained on the 180 μm screen was oxidized for 5 minutes in hot Schulze solution with a base neutralization to release the palynomorphs, then screened through 180 μm and 10 μm screens, mounted as slide B (L. Dancey, pers. comm., 2 December 2004), and analyzed separately.

In order to permit comparison of the palynological data from oxidized and kerogen fractions of the same sample, 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 acetolyzed 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. A comparison of palynomorph yield from kerogen samples and from acetolyzed preparations from the kerogen samples at depths 580 m, 590 m, and 600 m is presented in Table 3.

Counting and summation procedures

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 m and 900 m, yielding 82.12 ± 36.5 palynomorphs per sample. Samples at 140 m, 150 m, and 160 m were barren. The oxidized fraction was scanned for palynomorphs and taxa were recorded as presence or absence data.

Taxa identified in the kerogen fraction of Mallik 5L-38 well were allocated to various groups of biostratigraphic or ecological significance (Table 4). Some taxa may occur in more than one category, i.e. as both an angiosperm and

Table 3. Comparison of palynomorph assemblages from kerogen and acetolyzed kerogen preparations for Mallik 5L-38 samples 580 m, 590 m, and 600 m. Prop. = proportional, Diff. = difference, T-C-T = Taxodiaceae-Cupressaceae-Taxaceae.

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.
<i>Lycopodium</i> spike	53.0			119.0				
Alga	1.0	2.9	0.02	1.0	1.6	0.01	1.2	0.01
<i>Anatolinites</i> sp.				1.0				
<i>Alnus</i> 4-porate				2.0	3.2	0.02	3.2	0.02
<i>Alnus</i> 5-porate	1.0	2.9	0.02	1.0	1.6	0.01	1.2	0.01
<i>Alnus</i> 6-porate				1.0				
<i>Betula</i> ≤20 μm				2.0	3.2	0.02	3.2	0.02
<i>Betula</i> >20 μm								
(?) <i>Cedrus</i>								
<i>Corylus</i> -type								
<i>Deltoidospora</i> sp.				2.0	3.2	0.02	3.2	0.02
Dinoflagellate indet.								
Ericales	1.0	2.9	0.02				2.9	0.02
<i>Fractisporonites</i> sp.	1.0							
Fungal hyphae								
<i>Inapertisporites dubius</i>	3.0	8.6	0.06				8.6	0.06
<i>Inapertisporites</i> sp. (fungal)	1.0							
(?) <i>Larix-Pseudotsuga</i>				4.0	6.5	0.03	6.5	0.03
<i>Laevigatosporites</i> sp.	1.0	2.9	0.02	2.0	3.2	0.02	0.4	0.00
Liliacidites								
<i>Osmunda</i> sp.								
(?) <i>Paraalnipollentias alterniporus</i>				1.0				
<i>Picea</i> sp.								
<i>Pinus</i> 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
<i>Polyadosporites</i> sp.								
<i>Pterocarya</i> sp.				1.0				
Recycled palynomorphs	5.0	14.3	0.09	8.0	12.9	0.07	1.4	0.03
<i>Retitricolpites</i> sp.				1.0				
(?) <i>Sciadopitys</i>								
<i>Sparganium</i> sp.				1.0				
<i>Sphagnum</i> 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
<i>Tricolpites</i> sp.								
<i>Tripoporollentias</i> sp.				3.0	4.8	0.03	4.8	0.03
<i>Tsuga canadensis</i> -type								
<i>Ulmus</i> -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				

an angiosperm with temperate climatic affinities. The “1” in Table 4 indicates the category of the taxon, 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 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 Basin mid- and Late Cenozoic palynology because of the modernization of the flora in the Eocene (*see* above) and because there may be minimal thermal maturity or preservational differences between contemporaneous and

Table 3. Continued.

Mallik 5L-38, 590 m								
Taxon	P4672-97 Kerogen			P4672-97c Acetolysis			Difference	
	Count	%	Count/ spike	Count	%	Prop. Count/ spike	Absolute % Diff.	Absolute Prop. Diff.
<i>Lycopodium</i> spike	92.0			141.0				
Alga	1.0	2.0	0.01				2.0	0.01
<i>Alnus</i> 4-porate				1.0	1.6	0.01	1.6	0.01
<i>Alnus</i> 5-porate	2.0	4.1	0.02	1.0	1.6	0.01	2.5	0.01
<i>Betula</i> ≤20 µm								
<i>Betula</i> >20 µm				2.0	3.2	0.01	3.2	0.01
(?) <i>Cedrus</i>								
<i>Corylus</i> -type				1.0	1.6	0.01	1.6	0.01
<i>Deltoidospora</i> sp.	1.0	2.0	0.01	4.0	6.5	0.03	4.4	0.02
Dinoflagellate indet.				1.0				
Ericales								
Fungal hyphae								
<i>Inapertisporites dubius</i>	3.0	6.1	0.03	1.0	1.6	0.01	4.5	0.03
<i>Inapertisporites</i> sp. (fungal)	1.0			3.0				
(?) <i>Larix-Pseudotsuga</i>	1.0	2.0	0.01				2.0	0.01
<i>Laevigatosporites</i> sp.				4.0	6.5	0.03	6.5	0.03
Liliacidites								
<i>Osmunda</i> sp.								
<i>Picea</i>				2.0	3.2	0.01	3.2	0.01
<i>Pinus</i>	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
<i>Polyadosporites</i> sp.								
Recycled palynomorphs	3.0	6.1	0.03	9.0	14.5	0.06	8.4	0.03
(?) <i>Sciadopitys</i>								
<i>Sphagnum</i> 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
<i>Tricolpites</i> sp.	1.0	2.0	0.01					
<i>Triporopollentis</i> sp.	1.0	2.0	0.01	3.0	4.8	0.02	2.8	0.01
<i>Tsuga canadensis</i> -type								
<i>Ulmus</i> -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				

recycled palynomorphs. 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 among definitely recycled, suspect recycled, and contemporaneous palynomorphs. These patterns can then be interpreted with regard to the integrity of the pollen record and correlated with regional and global events.

Calculation of pollen ratios

Pollen ratios of selected pollen taxa were calculated for Mallik 5L-38 well 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 the Mallik 2L-38 well. A three-point moving average function has been applied to all

Table 3. Continued.

Mallik 5L-38, 600 m								
Taxon	P4672-99 Kerogen			P4672-99c Acetolysis			Difference	
	Count	%	Count/ spike	Count	%	Prop. Count/ spike	Absolute % Diff.	Absolute Prop. Diff.
<i>Lycopodium</i> spike	38.0			118.0				
Alga				2.0	2.1	0.02	2.1	0.02
<i>Alnus</i> 4-porate	2.0	7.1	0.05	7.0	7.3	0.06	0.1	0.01
<i>Alnus</i> 5-porate	1.0	3.6	0.03	2.0	2.1	0.02	1.5	0.01
<i>Betula</i> ≤20 μm								
<i>Betula</i> >20 μm				3.0	3.1	0.03	3.1	0.03
(?) <i>Cedrus</i>				1.0	1.0	0.01	1.0	0.01
<i>Corylus</i> -type				1.0	1.0	0.01	1.0	0.01
<i>Deltoidospora</i> 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
<i>Inapertisporites dubius</i>	1.0	3.6	0.03	3.0	3.1	0.03	0.4	0.00
(?) <i>Larix-Pseudotsuga</i>				1.0	1.0	0.01	1.0	0.01
<i>Laevigatosporites</i> 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
<i>Osmunda</i> sp.				1.0	1.0	0.01	1.0	0.01
<i>Picea</i> sp.				2.0	2.1	0.02	2.1	0.02
<i>Pinus</i> 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
<i>Polyadosporites</i> 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
(?) <i>Sciadopitys</i>				1.0	1.0	0.01	1.0	0.01
<i>Sphagnum</i> 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
<i>Triporopollentias</i> sp.	1.0	3.6	0.03	2.0	2.1	0.02	1.5	0.01
<i>Tsuga canadensis</i> -type				2.0	2.1	0.02	2.1	0.02
<i>Ulmus</i> -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 well.

Taxa summation categories and references		Recycled palynomorphs	Marine and/or aquatic palynomorphs				Terrestrial palynomorphs				
'Kerogen' taxa	Affinity	Recycled	Dinoflagellates cysts	Algae	Foraminiferal and scolecodonts	Fungi	Bryophyte	Ferns and allies	Gymnosperms	Angiosperms	Temperate angiosperms
<i>Michrystidium</i> sp.	AC			1							
<i>Veryhachium</i> sp.	AC	1									
<i>Ovoidites ligneolus</i>	AL			1							
<i>Sigmopollis carbonis</i>	AL			1							
<i>Sigmopollis</i> sp.	AL			1							
Algae spp.	IN			1							
Dinoflagellate indet.	DC	1	?								
<i>Filisphaera filifera</i>	DC		1								
<i>Labyrinthodinium truncatum</i>	DC		1								
<i>Odontochitina operculata</i>	DC	1	?								
Peridinioid dinoflagellate	DC		1								
<i>Polysphaeridium zoharyi</i>	DC	?	1								
<i>Spiniferites</i> sp.	DC		1								
Microforaminiferal test lining	FO				1						
<i>Brachysporisporites</i> sp.	FU					1					
<i>Dicellaesporites</i> sp.	FU					1					
<i>Diporisporites</i> sp.	FU					1					
<i>Foveodiporites</i> sp.	FU					1					
<i>Fractisporonites</i> sp.	FU					1					
Fungi hyphae	FU					1					
<i>Hypoxylonites</i> sp.	FU					1					
<i>Inapertisporites</i> sp.	FU					1					
<i>Involutisporonites</i> sp.	FU					1					
<i>Lacrimasporonites</i> sp.	FU					1					
<i>Monoporisporites</i> sp.	FU					1					
<i>Multicellaesporites</i> sp.	FU					1					
<i>Multicellites</i> sp.	FU					1					
<i>Papulosporonites</i> sp.	FU					1					
<i>Polyadosporites</i> spp.	FU					1					
<i>Reduviasporonites</i> sp.	FU					1					
<i>Striadiporites inflexus</i>	FU					1					
<i>Striadiporites multistriatus</i>	FU					1					
<i>Trichopeltina</i> sp.	FU					1					
Unknown spp.	FU					1					
Scolecodont	MP				1						
<i>Abies</i> sp.	SP								1		
<i>Acer</i> sp.	SP										1
<i>Alnus</i> 3-porate	SP									1	
<i>Alnus</i> 4-porate	SP									1	
<i>Alnus</i> 5-porate	SP									1	
<i>Alnus</i> 6-porate	SP									1	
Apiaceae	SP									1	

AC = acritarch, ALIN = Algae, DC = dinoflagellate cyst, FO = foraminifera, FU = fungus, MP = miscellaneous palynomorph, SP = spore or pollen, * = designation used to hold co-ordinates of unusual specimens on a slide, without implying that they are the same entity from sample to sample. ? = uncertain

Table 4. Continued.

Taxa summation categories and references		Recycled palynomorphs	Marine and/or aquatic palynomorphs					Terrestrial palynomorphs				
'Kerogen' taxa	Affinity	Recycled	Dinoflagellates cysts	Algae	Foraminiferal and scolecodonts	Fungi	Bryophyte	Ferns and allies	Gymnosperms	Angiosperms	Temperate angiosperms	
<i>Araucariacites australis</i>	SP	1										
<i>Arecipites symmetricus</i>	SP									1		
<i>Artemisia</i> sp.	SP									1		
Asteraceae	SP									1		
<i>Baculatisporites crassiprimarius</i>	SP							1				
<i>Baculatisporites quintus</i>	SP							1				
<i>Baculatisporites</i> sp.	SP							1				
<i>Betula</i> ≤ 20 μm	SP									1		
<i>Betula</i> >20 μm	SP									1		
<i>Callistopollenites</i> sp.	SP	1										
<i>Carya</i> sp.	SP										1	
Caryophyllaceae	SP									1		
Chenopodiineae	SP									1		
<i>Cicatricosisporites australiensis</i>	SP	?						1				
<i>Cicatricosisporites hallei</i>	SP	?						1				
<i>Cicatricosisporites paradorogensis</i>	SP	?						1				
<i>Cicatricosisporites</i> sp.	SP	?						1				
<i>Cicatricosisporites spiralis</i>	SP	?						1				
<i>Classopollis classoides</i>	SP	1										
<i>Corylus</i> -type	SP									1		
<i>Deltoidospora</i> sp.	SP	?						1				
<i>Diervilla-Weigela</i> sp.	SP									1		
<i>Distaltriangulisporites perplexus</i>	SP	1										
<i>Equisetum</i> sp.	SP							1				
Ericales	SP									1		
<i>Gleicheniidites senonicus</i>	SP	1						1				
<i>Hamulatisporis</i> sp.	SP	?						1				
<i>Ilex</i> -type	SP										1	
<i>Inaperturopollenites dubius</i>	SP	?							1			
Iridaceae-Liliaceae	SP									1		
<i>Klukisporites foveolatus</i>	SP	1						?				
<i>Kurtzipites</i> sp.	SP	1										
<i>Labrapollis</i> sp.	SP									1		
<i>Laevigatosporites</i> sp.	SP							1				
<i>Larix-Pseudotsuga</i> -type	SP								1			
<i>Lycopodium annotinum-complanatum</i>	SP							1				
<i>Lycopodium</i> sp.	SP							1				
<i>Lycopodium</i> spike	SP											
<i>Magnolia</i> 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		
<i>Momipites wyomingensis</i>	SP	?								1		
Onagraceae	SP									1		
<i>Osmunda</i> sp.	SP							1				

Table 4. Continued.

Taxa summation categories and references		Recycled palynomorphs	Marine and/or aquatic palynomorphs				Terrestrial palynomorphs				
	Affinity	Recycled	Dinoflagellates cysts	Algae	Foraminiferal and solecodonts	Fungi	Bryophyte	Ferns and allies	Gymnosperms	Angiosperms	Temperate angiosperms
'Kerogen' taxa											
<i>Picea</i> sp.	SP								1		
Pinaceae	SP								1		
<i>Pinus koraiensis</i> -type	SP								1		
<i>Pinus</i> sp.	SP								1		
<i>Pistillipollenites macgregorii</i>	SP									1	
Poaceae	SP									1	
<i>Podocarpus</i> -type	SP								1		
Polypodiaceae-Dennstaedtiaceae form 1	SP							1			
Polypodiaceae-Dennstaedtiaceae form 2	SP							1			
<i>Pterocarya</i> sp.	SP										1
Recycled palynomorphs	SP	1									
<i>Reticulosporis</i> sp.	SP							1			
<i>Retimonocolpites</i> sp.	SP									1	
<i>Retitricolpites</i> sp.	SP									1	
<i>Sciadopitys</i> sp.	SP								1		
<i>Selaginella microdendron</i> -type	SP							1			
<i>Selaginella selaginoides</i>	SP							1			
<i>Selaginella</i> sp.	SP							1			
<i>Shepherdia canadensis</i> -type	SP									1	
<i>Sparganium</i> sp.	SP									1	
<i>Sphagnum</i> sp.	SP	?					1				
<i>Stereisporites antiquasporites</i>	SP	?					1				
<i>Stereisporites maximalis</i>	SP	?					1				
<i>Stereisporites microgranulus</i>	SP	?					1				
Taxodiaceae-Cupressaceae-Taxaceae	SP	?							1		
Tetrad pollen (scabrate)	SP									1	
Tetraporate spp.	SP									1	
<i>Tilia</i> -type	SP										1
<i>Triatriopollenites granilabratus</i>	SP									1	
<i>Triatriopollenites pulcher</i>	SP									1	
<i>Tricolpites</i> sp.	SP									1	
<i>Tricolpopollenites</i> sp.	SP									1	
<i>Tricolporopollenites</i> sp.	SP									1	
Triporate type D of Parsons (2000)	SP	?								1	
<i>Triporopollenites</i> sp.	SP									1	
<i>Tsuga-canadensis</i> -type	SP							1			
<i>Tsuga</i> sp.	SP							1			
Tubuliflorae	SP									1	
<i>Ulmus</i> -type	SP										1
Undeterminable spp.	SP										
Unknown sp. A, B, and C *	SP										
Unknown spp.	SP										
<i>Verrucosiporites obscurilaesuratus</i>	SP							1			
<i>Vitreisporites pallidus</i>	SP										

AC = acritarch, ALIN = algae, DC = dinoflagellate cyst, FO = foraminifera, FU = fungus, MP = miscellaneous palynomorph, SP = spore or pollen, * = designation used to hold co-ordinates of unusual specimens on a slide, without implying that they are the same entity from sample to sample. ? = uncertain

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 Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae ratio may reflect a warm to cool climatic trend. Of all the ratios, this is based on the most abundant pollen. The Taxodiaceae-Cupressaceae-Taxaceae 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 that appears to have Taxodiaceae-Cupressaceae-Taxaceae affinities, and it is included in the Taxodiaceae-Cupressaceae-Taxaceae category, but the curve of Taxodiaceae-Cupressaceae-Taxaceae minus *Inaperturosporites dubius*/Pinaceae has also been calculated for comparison with the former curves. (The ratios Taxodiaceae-Cupressaceae-Taxaceae /Pinaceae and Taxodiaceae-Cupressaceae-Taxaceae minus *Inaperturosporites dubius*/Pinaceae, (below) are very similar, arguing that the grains classified as *I. dubius* are indeed Taxodiaceae-Cupressaceae-Taxaceae 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, nonthermophilous taxa such as *Alnus*, *Betula*, other triporate pollen, and Ericales. In the analysis of Mallik 2L-38 well, a curve of (temperate angiosperms) – *Ulmus*-type was generated, and it is also calculated here for comparison (see Fig. 11).

Pinus and *Picea* are the most abundant Pinaceae pollen in the Mallik 2L-38 well. In modern Pinaceae, both *Pinus* and *Picea* 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 (nonrecycled) 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 well results with the Mallik 2L-38 well 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 recorded in temperate and northern Cenozoic sediment 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 following 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 that 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 sandstone beds 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 (*see below*; White, 2009).

Erosion, transport, and deposition of recycled palynomorphs

Recycled pollen and spores enter the palynomorph 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 (*see below*). An additional source of recycled palynomorphs is mudstone or shale, 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 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 to 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 levées.

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 well analysis is a complement to the analysis of the Mallik 2L-38 well, within the general objective of analyzing kerogen in both wells; however, preparation techniques were adjusted in this study to overcome problems of poor palynomorph recovery. 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 Mallik 5L-38 and Mallik 2L-38 wells comparable, and 2) do the Mallik 5L-38 kerogen and +180 μm fractions differ and if so, why?

A comparison of processing techniques for the Mallik 2L-38 and Mallik 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 about 210 μm 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 almost all palynomorphs, was washed away. The kerogen fraction was then given a light oxidation with cold sodium hypochlorite and neutralized with ammonium hydroxide to improve palynomorph concentration by removing fine detritus, and this fraction was analyzed. For Mallik 5L-38 samples, the kerogen fraction was used for analysis of contemporaneous pollen, but this fraction did not receive cold sodium hypochlorite treatment. The chief difference between Mallik 2L-38 and Mallik 5L-38 well sample processing was that for Mallik 5L-38, from 450 m to 900 m, the +180 μm fraction was retained and its palynomorphs released by strong oxidation. This step yielded separate 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 Mallik 2L-38 and Mallik 5L-38 analyses. Hence the question, in Mallik 2L-38, could the brief treatment of cold sodium hypochlorite and base have released into the kerogen residue the recycled palynomorphs that were excluded in the Mallik 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, full strength bleach treatment left much of the coal unmacerated and released perhaps 5% of the palynomorphs released by the Schulze solution. Continuing the experiment with a treatment that is a similar, but a longer bleaching, than given the original Mallik 2L-38 samples, the same coal was crushed and treated with a cold, dilute bleach solution (~5%, sodium hypochlorite) for 5 minutes and then a base. This preparation gave a minimal yield of two or three 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 Mallik 2L-28 samples by the light sodium hypochlorite treatment of any organic clasts that passed through the 180 μm screen, although one

cannot rule out any contamination. Therefore, it seems likely that light sodium hypochlorite and base treatment in Mallik 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 Mallik 2L-38 preparations, and by hand in the Mallik 5L-38 preparations. The high-energy ultrasonic probe conceivably reduced organic clasts in Mallik 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 Mallik 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 December 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 Mallik 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 previously; however, one must examine how these fractions differ and if there might have been crosscontamination between fractions during processing.

Species lists suggest that minimal crosscontamination 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 acetolyzed *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 acetolyzed *Lycopodium* spores from the exotic spike tablets. This evidence demonstrates 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 or

absence (nominal) data, collected to taxonomically characterize that fraction. Consequently, comparisons must be on the basis of presence or absence data.

Comparison of taxa can be done by inspection of the plot of Mallik 5L-38 palynomorph data (Fig. 3 oversized) plotted alphabetically by group. This relative abundance plot presents the occurrences of taxa along with the qualifier, “?,” to denote uncertain identifications. In this plot, samples from 450 m 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*-type occur in the kerogen fraction. Other taxa occur mostly in the +180 μm fraction, e.g. *Sciadopitys* sp., *Hamulatisporis* sp., *Gleicheniidites senonicus*, and 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, 1993, 1995, 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. Corresponding analysis 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 m and 513.66 m were outliers on axis 1, which have a disproportionate effect on correspondence analysis (Kovach, 1995). 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 thus 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 (Fig. 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. 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 m was eliminated from the analysis as an outlier, because of its limited species list. In sample 690 m, the *Kurtzipites* specimen is eroded and the identification uncertain.

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

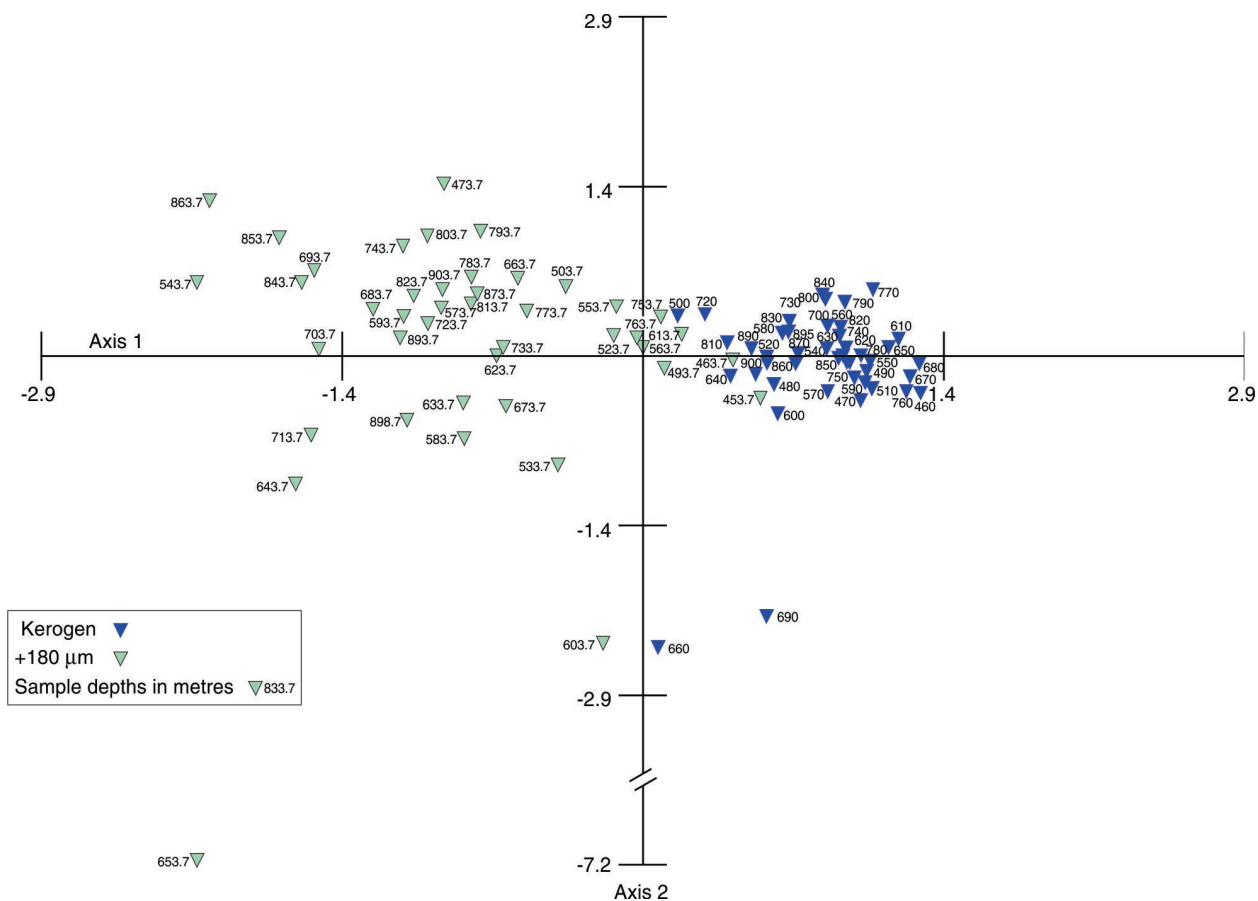


Figure 4. Axes 1 and 2 from correspondence analysis results of the Mallik 5L-38 well pollen and filicale spore taxa, samples from 450 m to 900 m with paired kerogen +180 μm analyses that are designated as 3.66 m below their true depth. Samples 483.66 m and 513.66 m are omitted, as are taxa with only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

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

Samples sorted by axis 1 scores			Taxa sorted by axis 1 scores	
Sample depth (m)	Groups	Axis 1	Taxa	Axis 1
543.66	+180 µm	-2.139	<i>Castanea</i> -type	-3.489
653.66	+180 µm	-2.138	Sum <i>Celtis</i>	-3.229
863.66	+180 µm	-2.077	<i>Pistillipollenites macgregorii</i>	-2.903
833.66	+180 µm	-1.851	<i>Podocarpus</i> -type	-2.87
853.66	+180 µm	-1.744	<i>Triatriopollenites pulcher</i>	-2.798
643.66	+180 µm	-1.665	<i>Hazaria sheopiarii</i>	-2.74
843.66	+180 µm	-1.637	<i>Pachysandra-Sarcococca (Erdtmanipollis procumbentiformis)</i>	-2.708
713.66	+180 µm	-1.592	<i>Pristinuspollenites</i> sp.	-2.608
693.66	+180 µm	-1.576	<i>Cranwellia</i> sp.	-2.531
703.66	+180 µm	-1.555	Sum <i>Azonia</i>	-2.296
683.66	+180 µm	-1.294	Sum <i>Distaltriangulisporites</i>	-2.219
893.66	+180 µm	-1.164	Apiaceae	-2.167
743.66	+180 µm	-1.151	<i>Paraalnipollenites alterniporus</i>	-2.123
593.66	+180 µm	-1.147	<i>Striatocarpus</i> sp.	-1.995
898.66	+180 µm	-1.132	<i>Sciadopitys</i> sp.	-1.993
823.66	+180 µm	-1.099	<i>Rousea</i> sp.	-1.916
803.66	+180 µm	-1.033	Sum <i>Wodehouseia</i>	-1.909
723.66	+180 µm	-1.031	<i>Retimonocolpites</i> sp.	-1.774
573.66	+180 µm	-0.966	<i>Hamulatisporis</i> sp.	-1.675
903.66	+180 µm	-0.961	<i>Retitricolpites</i> sp.	-1.633
473.66	+180 µm	-0.954	Rosaceae	-1.603
633.66	+180 µm	-0.861	<i>Retitricolporopollenites</i> sp.	-1.556
583.66	+180 µm	-0.857	<i>Appendicisporites</i> sp.	-1.546
813.66	+180 µm	-0.824	<i>Tricolpopollenites</i> sp.	-1.514
783.66	+180 µm	-0.823	Sum <i>Stereisporites</i>	-1.49
873.66	+180 µm	-0.794	<i>Triatriopollenites granilabratus</i>	-1.447
793.66	+180 µm	-0.779	<i>Carya</i> sp.	-1.338
623.66	+180 µm	-0.701	Sum <i>Cicatricosisporites</i>	-1.293
733.66	+180 µm	-0.67	Iridaceae-Liliaceae sp.	-1.283
673.66	+180 µm	-0.657	<i>Vitreisporites pallidus</i>	-1.271
663.66	+180 µm	-0.6	Sum <i>Gleicheniidites</i>	-1.247
773.66	+180 µm	-0.558	Sum Polypodiaceae-Dennstaedtiaceae	-1.219
533.66	+180 µm	-0.407	<i>Ilex</i> -type	-1.205
503.66	+180 µm	-0.37	<i>Quercus</i> sp.	-1.159
603.66	+180 µm	-0.234	Sum <i>Lycopodium</i>	-0.925
523.66	+180 µm	-0.141	<i>Pinus koraiensis</i> -type	-0.849
553.66	+180 µm	-0.127	<i>Osmunda</i> sp.	-0.626
763.66	+180 µm	-0.029	<i>Sparganium</i> sp.	-0.367
563.66	+180 µm	0	<i>Tilia</i> -type	-0.203
660	Kerogen	0.073	Ericales	-0.16
753.66	+180 µm	0.085	<i>Ulmus</i> -type	-0.095
493.66	+180 µm	0.102	<i>Sphagnum</i> sp.	-0.053
500	Kerogen	0.167	Tetrad pollen (scabrate)	-0.011
613.66	+180 µm	0.185	<i>Tricolpites</i> sp.	0.02
720	Kerogen	0.298	Taxodiaceae-Cupressaceae-Taxaceae	0.094
810	Kerogen	0.404	<i>Magnolia</i> sp.	0.101
640	Kerogen	0.42	Sum <i>Selaginella</i>	0.122
463.66	+180 µm	0.431	<i>Inaperturopollenites dubius</i>	0.148
890	Kerogen	0.52	<i>Laevigatosporites</i> sp.	0.161
900	Kerogen	0.54	<i>Tripoporopollenites</i> sp.	0.287
453.66	+180 µm	0.563	<i>Momipites wyomingensis</i>	0.323

Table 5. Continued.

Samples sorted by axis 1 scores			Taxa sorted by axis 1 scores	
Sample depth (m)	Groups	Axis 1	Taxa	Axis 1
520	Kerogen	0.593	<i>Picea</i> sp.	0.339
690	Kerogen	0.593	<i>Pinus</i> sp.	0.339
860	Kerogen	0.595	<i>Deltoidospora</i> sp.	0.398
480	Kerogen	0.627	<i>Larix-Pseudotsuga</i> -type	0.562
600	Kerogen	0.647	Sum <i>Alnus</i>	0.817
580	Kerogen	0.668	<i>Pterocarya</i> sp.	0.821
830	Kerogen	0.698	Pinaceae	0.881
730	Kerogen	0.702	<i>Tsuga canadensis</i> -type	0.887
895	Kerogen	0.732	<i>Baculatisporites quintus</i>	0.937
870	Kerogen	0.744	<i>Tricolporopollenites</i> sp.	0.97
840	Kerogen	0.862	<i>Acer</i> sp.	0.978
800	Kerogen	0.875	<i>Betula</i> >20 µm	1.065
630	Kerogen	0.881	<i>Kurtzipites</i> sp.	1.186
570	Kerogen	0.885	<i>Corylus</i> -type	1.292
700	Kerogen	0.885	<i>Abies</i> sp.	1.324
850	Kerogen	0.938	<i>Tsuga</i> sp.	1.349
820	Kerogen	0.941	<i>Baculatisporites crassiprimarius</i>	1.49
560	Kerogen	0.947	Tetraporate spp.	1.623
780	Kerogen	0.959	<i>Arecipites symmetricus</i>	1.655
790	Kerogen	0.968	Chenopodiineae	1.657
740	Kerogen	0.973	<i>Betula</i> ≤20 µm	1.794
750	Kerogen	0.973	<i>Shepherdia canadensis</i> -type	1.988
450	Kerogen	0.977	<i>Classopollis classoides</i>	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		

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
Cumulative per cent	7.581	13.002	18.141	22.207	26.173	29.818	33.329	36.657	39.909	42.95

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 sheopariiae* 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 or 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 taxa it is uncertain if it is correct to interpret an occurrence as recycled, or as constituting a legitimate occurrence within its

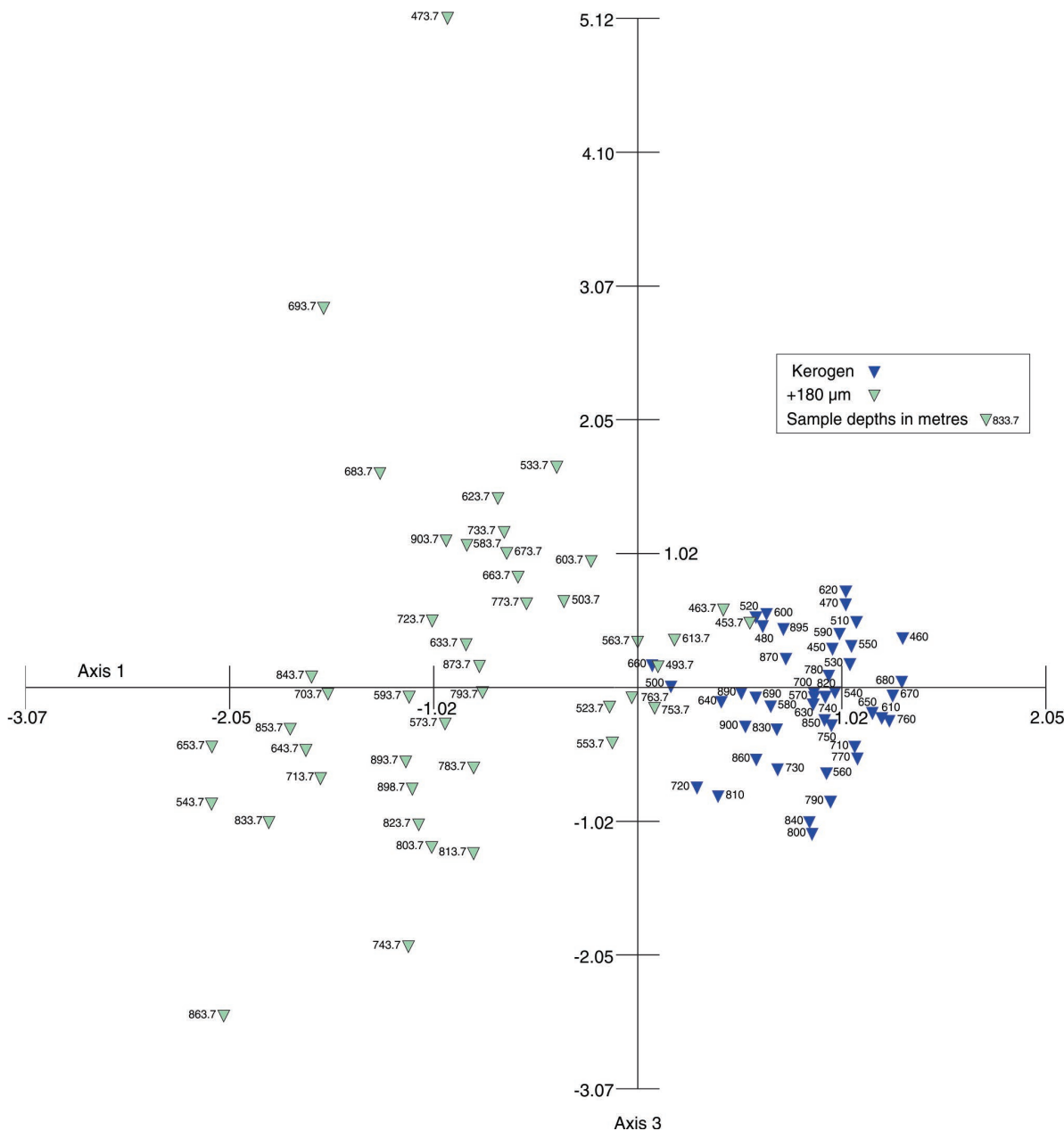


Figure 5. Axes 1 and 3 from correspondence analysis results of the Mallik 5L-38 well pollen and filicale spore taxa, samples from 450 m to 900 m with paired kerogen = 180 µm analyses that are designated as 3.66 m below their true depth. Samples 483.66 m and 513.66 m are omitted, as are taxa with only 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.

stratigraphic range. For example, in the Caribou Hills sections, *Triatriopollenites granilabratus* occurs in the zones CHE1 (Late Paleocene) to lower 4b (Early to Middle and (?)Late Eocene) (Parsons, 2000). (White (2009) has argued that the uppermost portion of CHE4b may be Late Eocene.) *Triatriopollenites pulcher* occurs in zones CHE3 (Early to Middle Eocene) to 4c (Late Eocene or (?)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 cannot 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 upward 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 Maastrichtian–Danian (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 post-Cretaceous strata (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 that +180 μm and kerogen fractions of the organic matter contain 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. Correspondence analysis supports the original intent to analyze 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 flood-plain 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 analyze 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 13–20 g to kerogen if it is possible to obtain a larger sample.
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 sodium hypochlorite 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 that are likely recycled, for

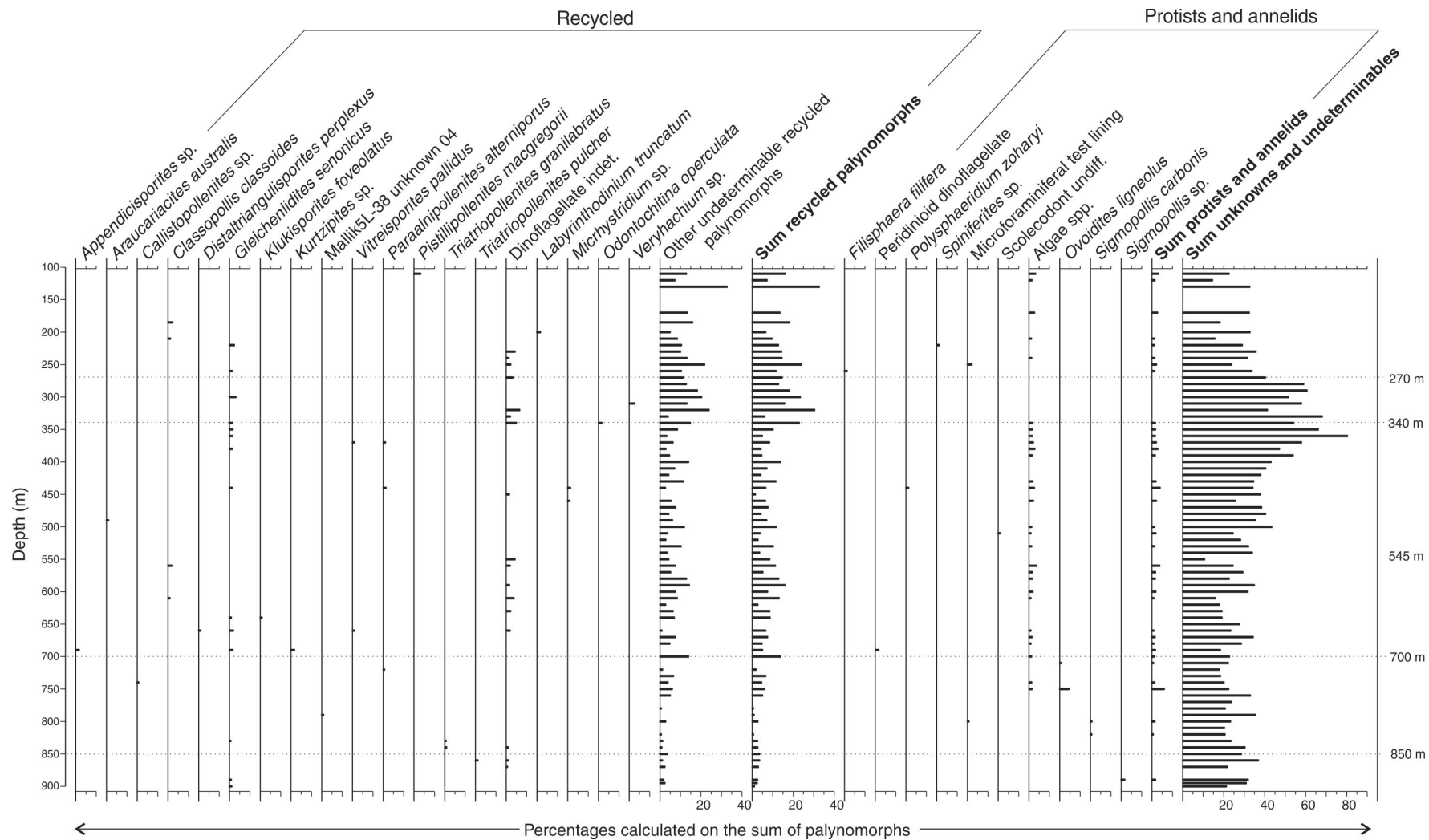


Figure 6. Recycled taxa, protists and annelids, and unknown and undeterminable palynomorphs in the cutting kerogen fraction, 105–900 m.

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

Age range of selected, probably recycled palynomorphs in Mallik 5L-38 well, sorted by depth							
Depth (m)	Taxon	Approximate age from literature		Approximate age (Ma)			Location
		Lower	Upper	Lower age (Ma)	Upper age (Ma)	Reference	
110	<i>Pistillipollenites macgregorii</i>	Chron 26n	Late Eocene	60	34	GSC Paleontological Report 11-ARS-1998; White, 2009	Ellesmere Island, Beaufort-Mackenzie region
185	<i>Classopollis classoides</i>	Early Triassic	Paleocene	245	55	White et al., 2002; A.R. Sweet, pers. comm., 2004	Global, Alberta
210	<i>Classopollis classoides</i>	Early Triassic	Paleocene	245	55	White et al., 2002; A.R. Sweet, pers. comm., 2005	Global, Alberta
370	<i>Paraalnipollenites alterniporus</i>	Paleocene	Late Eocene, (?)Oligocene	65	34	Rouse, 1977; Ioannides and McIntyre, 1980; Long and Sweet, 1994; Parsons, 2000; Palynodata Inc. and White, 2008	Eurasia and North America, north of 20°
370	<i>Vitreisporites pallidus</i>	J1 ₃	Campanian	183	70	Pocock, 1970a, b; A.R. Sweet, pers. comm., 2004	Alberta
440	<i>Paraalnipollenites alterniporus</i>	Paleocene	Late Eocene, (?)Oligocene	65	34	Rouse, 1977; Ioannides and McIntyre, 1980; Long and Sweet, 1994; Parsons, 2000; Palynodata Inc. and White, 2008	Eurasia and N America, north of 20°
460	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
473.66	<i>Wodehouseia spinata</i>	Chron 30n	Chron 28n	66	62	11-ARS-1998	Alberta
473.66	<i>Cranwellia</i> sp.	late Campanian	Paleocene	76	56	Nichols and Sweet, 1993	Alberta
473.66	<i>Azonia</i> sp.	(?)Coniacian	Late Maastrichtian	89	65	Nichols and Sweet, 1993	Western interior N. America
483.66	<i>Paraalnipollenites alterniporus</i>	Paleocene	Late Eocene, (?)Oligocene	65	34	Rouse, 1977; Ioannides and McIntyre, 1980; Long and Sweet, 1994; Parsons, 2000; Palynodata Inc. and White, 2008	Eurasia and N America, north of 20°
483.66	<i>Wodehouseia</i> sp.	Late Maastrichtian	Paleocene	67	55	Nichols and Sweet, 1993	Alberta
513.66	<i>Wodehouseia</i> sp.	Late Maastrichtian	Paleocene	67	55	Nichols and Sweet, 1993	Alberta
513.66	<i>Kurtzipites</i> sp.	Maastrichtian	Early Paleocene	71	61	Nichols and Sweet, 1993; A.R. Sweet, pers. comm., 2004	Yukon and N.W.T.
533.66	<i>Vitreisporites pallidus</i>	J1 ₃	Campanian	183	70	Pocock, 1970a, b; A.R. Sweet, pers. comm., 2004	Alberta
543.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.

Table 6. Continued.

Age range of selected, probably recycled palynomorphs in Mallik 5L-38 well, sorted by depth							
Depth (m)	Taxon	Approximate age from literature		Approximate age (Ma)			Location
		Lower	Upper	Lower age (Ma)	Upper age (Ma)	Reference	
543.66	<i>Paraalnipollenites alterniporus</i>	Paleocene	Late Eocene, (?)Oligocene	65	34	Rouse, 1977; Ioannides and McIntyre, 1980; Long and Sweet, 1994; Parsons, 2000; Palynodata Inc. and White, 2008	Eurasia and N America, north of 20°
543.66	<i>Hazaria sheopariariae</i>	Campanian	Paleocene	84	55	Srivastava, 1971; A.R. Sweet, pers. comm., 2004	Alberta
553.66	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
553.66	<i>Hazaria sheopariariae</i>	Campanian	Paleocene	84	55	Srivastava, 1971; A.R. Sweet, pers. comm., 2004	Alberta
560	<i>Classopollis classoides</i>	Early Triassic	Paleocene	245	55	White et al., 2002; A.R. Sweet, pers. comm., 30 Dec. 2006	Global, Alberta
573.66	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 30 Dec. 2006	Wyoming
573.66	<i>Hazaria sheopariariae</i>	Campanian	Paleocene	84	55	Srivastava 1971; A.R. Sweet, pers. comm., 2004	Alberta
583.66	<i>Vitreisporites pallidus</i>	J1 ₃	Campanian	183	70	Pocock, 1970a, b; A.R. Sweet, pers. comm., 2004	Alberta
603.66	<i>Distaltriangulisporites perplexus</i>	Valanginian	Campanian	140	70	Burden and Hills, 1989; Payenberg et al., 2002	Alberta
610	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
610	<i>Classopollis classoides</i>	Early Triassic	Paleocene	245	55	White et al., 2002; A.R. Sweet, pers. comm., 2004	Global, Alberta
630	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
653.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
653.66	<i>Distaltriangulisporites irregularis</i>	Valanginian	Campanian	140	70	Burden and Hills, 1989; Payenberg et al., 2002	Alberta
653.66	<i>Distaltriangulisporites perplexus</i>	Valanginian	Campanian	140	70	Burden and Hills, 1989; Payenberg et al., 2002	Alberta
653.66	<i>Appendicisporites</i> sp.	Berriasian	Cenomanian	145	93	Burden and Hills, 1989; Singh, 1983	Alberta
660	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
660	<i>Distaltriangulisporites perplexus</i>	Valanginian	Campanian	140	70	Burden and Hills, 1989; Payenberg et al., 2002	Alberta
660	<i>Vitreisporites pallidus</i>	J1 ₃	Campanian	183	70	Pocock, 1970a, b; A.R. Sweet, pers. comm., 2004	Alberta
673.66	<i>Azonia pulchella</i>	Upper Santonian	Lower Maastrichtian	85	83	Wiggins, 1976	Alaska

Table 6. Continued.

Age range of selected, probably recycled palynomorphs in Mallik 5L-38 well, sorted by depth							
Depth (m)	Taxon	Approximate age from literature		Approximate age (Ma)			Location
		Lower	Upper	Lower age (Ma)	Upper age (Ma)	Reference	
673.66	<i>Vitreisporites pallidus</i>	J1 ₃	Campanian	183	70	Pocock, 1970a, b; A.R. Sweet, pers. comm., 2004	Alberta
683.66	<i>Tigrisporites</i> sp.	J2 ₁	Cenomanian	172	93	Pocock, 1970a, b; Singh, 1971, 1983	Alberta
683.66	<i>Vitreisporites pallidus</i>	J1 ₃	Campanian	183	70	Pocock, 1970a, b; A.R. Sweet, pers. comm., 2004	Alberta
690	<i>Kurtzipites</i> sp.	Maastrichtian	Early Paleocene	71	61	Nichols and Sweet, 1993; A.R. Sweet, pers. comm., 2004	Yukon and N.W.T.
690	<i>Appendicisporites</i> sp.	Berriasian	Cenomanian	145	93	Burden and Hills, 1989; Singh, 1983	Alberta
693.66	<i>Cranwellia</i> sp.	late Campanian	Paleocene	76	56	Nichols and Sweet, 1993	Alberta
693.66	<i>Azonia cribrata</i>	Assemblage 6, late Campanian	Assemblage 6, late Campanian	78	70	Nichols and Sweet, 1993	Bonnet Plume and Brackett basins
703.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
713.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
720	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
720	<i>Paraalnipollenites alterniporus</i>	Paleocene	Late Eocene, (?)Oligocene	65	34	Rouse, 1977; Ioannides and McIntyre, 1980; Long and Sweet, 1994; Parsons, 2000; Palynodata Inc. and White, 2008	Eurasia and North America, north of 20°
733.66	<i>Azonia</i> sp.	?Coniacian	Late Maastrichtian	89	65	Nichols and Sweet, 1993	Western interior North America
733.66	<i>Vitreisporites pallidus</i>	J1 ₃	Campanian	183	70	Pocock, 1970a, b; A.R. Sweet, pers. comm., 2004	Alberta
740	<i>Callistopollenites</i> sp.	Maastrichtian	Maastrichtian	71	65	Jansonius and Hills, 1977; A.R. Sweet, pers. comm., 2004	Alberta
743.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
743.66	<i>Triatriopollenites granilabratus</i>	CHE1	CHE lower 4b	60	40	Parsons, 2000	N.W.T.
743.66	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
770	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
780	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
783.66	<i>Kuylisporites lunaris</i>	Early Cretaceous	(?)Early Cretaceous	146	100	Singh, 1971	Alberta
790	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming

Table 6. Continued.

Age range of selected, probably recycled palynomorphs in Mallik 5L-38 well, sorted by depth							
Depth (m)	Taxon	Approximate age from literature		Approximate age (Ma)			Location
		Lower	Upper	Lower age (Ma)	Upper age (Ma)	Reference	
793.66	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
800	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
803.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
803.66	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
803.66	<i>Paraalnipollenites alterniporus</i>	Paleocene	Late Eocene, (?)Oligocene	65	34	Rouse, 1977; Ioannides and McIntyre, 1980; Long and Sweet, 1994; Parsons, 2000; Palynodata Inc. and White, 2008	Eurasia and N America, north of 20°
813.66	<i>Pistillipollenites macgregorii</i>	Chron 26n	Late Eocene	60	34	GSC Paleontological Report 11-ARS-1998; White, 2009	Ellesmere Island, Beaufort-Mackenzie region
813.66	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
823.66	Tricolpate type H of Parsons 2000	mid CHE3	CHE4c	44	28	Parsons, 2000	N.W.T.
823.66	<i>Triatriopollenites granilabratus</i>	CHE1	CHE lower 4b	60	40	Parsons, 2000	N.W.T.
823.66	<i>Singularia</i> sp.	Late Campanian	Maastrichtian	74	65	A.R. Sweet, pers. comm., 2004	Alberta
823.66	<i>Hazaria sheopariiae</i>	Campanian	Paleocene	84	55	Srivastava, 1971; A.R. Sweet, pers. comm., 2004	Alberta
830	<i>Triatriopollenites granilabratus</i>	CHE1	CHE lower 4b	60	40	Parsons, 2000	N.W.T.
833.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
840	Triporate type D of Parsons 2000	upper CHE2	CHE4b	56	34	Parsons, 2000	
840	<i>Triatriopollenites granilabratus</i>	CHE1	CHE lower 4b	60	40	Parsons, 2000	N.W.T.
840	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
843.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
843.66	<i>Paraalnipollenites alterniporus</i>	Paleocene	Late Eocene, (?)Oligocene	65	34	Rouse, 1977; Ioannides and McIntyre, 1980; Long and Sweet, 1994; Parsons, 2000; Palynodata Inc. and White, 2008	Eurasia and N America, north of 20°
843.66	<i>Hazaria sheopariiae</i>	Campanian	Paleocene	84	55	Srivastava, 1971; A.R. Sweet, pers. comm., 2004	Alberta

Table 6. Continued.

Age range of selected, probably recycled palynomorphs in Mallik 5L-38 well, sorted by depth							
Depth (m)	Taxon	Approximate age from literature		Approximate age (Ma)		Reference	Location
		Lower	Upper	Lower age (Ma)	Upper age (Ma)		
843.66	<i>Azonia</i> sp.	(?)Coniacian	Late Maastrichtian	89	65	Nichols and Sweet, 1993	Western interior N. America
853.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
853.66	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
853.66	<i>Azonia cribrata</i>	Assemblage 6, late Campanian	Assemblage 6, late Campanian	78	70	Nichols and Sweet, 1993	Bonnet Plume and Brackett basins
853.66	<i>Hazaria sheopiariae</i>	Campanian	Paleocene	84	55	Srivastava, 1971; A.R. Sweet, pers. comm., 2004	Alberta
860	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
860	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
863.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
863.66	<i>Pistillipollenites macgregorii</i>	Chron 26n	Late Eocene	60	34	GSC Paleontological Report 11-ARS-1998; White, 2009	Ellesmere Island, Beaufort-Mackenzie region
863.66	<i>Triatriopollenites granilabratus</i>	CHE1	CHE lower 4b	60	40	Parsons, 2000	N.W.T.
863.66	<i>Hazaria sheopiariae</i>	Campanian	Paleocene	84	55	Srivastava, 1971; A.R. Sweet, pers. comm., 2004	Alberta
873.66	<i>Paraalnipollenites alterniporus</i>	Paleocene	Late Eocene, (?)Oligocene	65	34	Rouse, 1977; Ioannides and McIntyre, 1980; Long and Sweet, 1994; Parsons, 2000; Palynodata Inc. and White, 2008	Eurasia and N. America, north of 20°
873.66	<i>Azonia cribrata</i>	Assemblage 6, late Campanian	Assemblage 6, late Campanian	78	70	Nichols and Sweet, 1993	Bonnet Plume and Brackett basins
890	<i>Momipites wyomingensis</i>	P2	Eocene	63	34	Nichols and Ott, 1978; A.R. Sweet, pers. comm., 2004	Wyoming
893.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
893.66	<i>Triatriopollenites granilabratus</i>	CHE1	CHE lower 4b	60	40	Parsons, 2000	N.W.T.
893.66	<i>Hazaria sheopiariae</i>	Campanian	Paleocene	84	55	Srivastava, 1971; A.R. Sweet, pers. comm., 2004	Alberta
893.66	<i>Aquilapollenites</i> sp.	(?)Coniacian-Santonian	Late Maastrichtian	86	65	Nichols and Sweet, 1993	Yukon and Northwest Territories
898.66	<i>Triatriopollenites pulcher</i>	CHE3	CHE4c	48	28	Parsons, 2000	N.W.T.
898.66	<i>Triatriopollenites granilabratus</i>	CHE1	CHE lower 4b	60	40	Parsons, 2000	N.W.T.

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 that 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 μm 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 coloured box 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*, which are dominantly Mesozoic taxa, but may occur in the Cenozoic. The genus *Classopollis* has a stratigraphic range up to the Eocene (Pocock and Jansonius, 1961) and *Vitreisporites pallidus* may occur as an autochthonous element in the Danian (Krutzschnig, 1967b).

The upper 450 m of the well (Fig. 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 predominantly from the Late Cretaceous to the Paleogene.

From 420 m to the 900 m there is a regular occurrence of taxa which are probably Cretaceous — dominantly Campanian or Maastrichtian; e.g. *Aquilapollenites* spp., *Azonia* spp., *Hazaria sheopariariae*, *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 the stratigraphic ranges of which are dominantly Cenozoic, including *Paraalnipollenites alterniporus* (also latest Maastrichtian; Nichols and Sweet, 1993), *Pistillipollenites macgregorii*, *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.

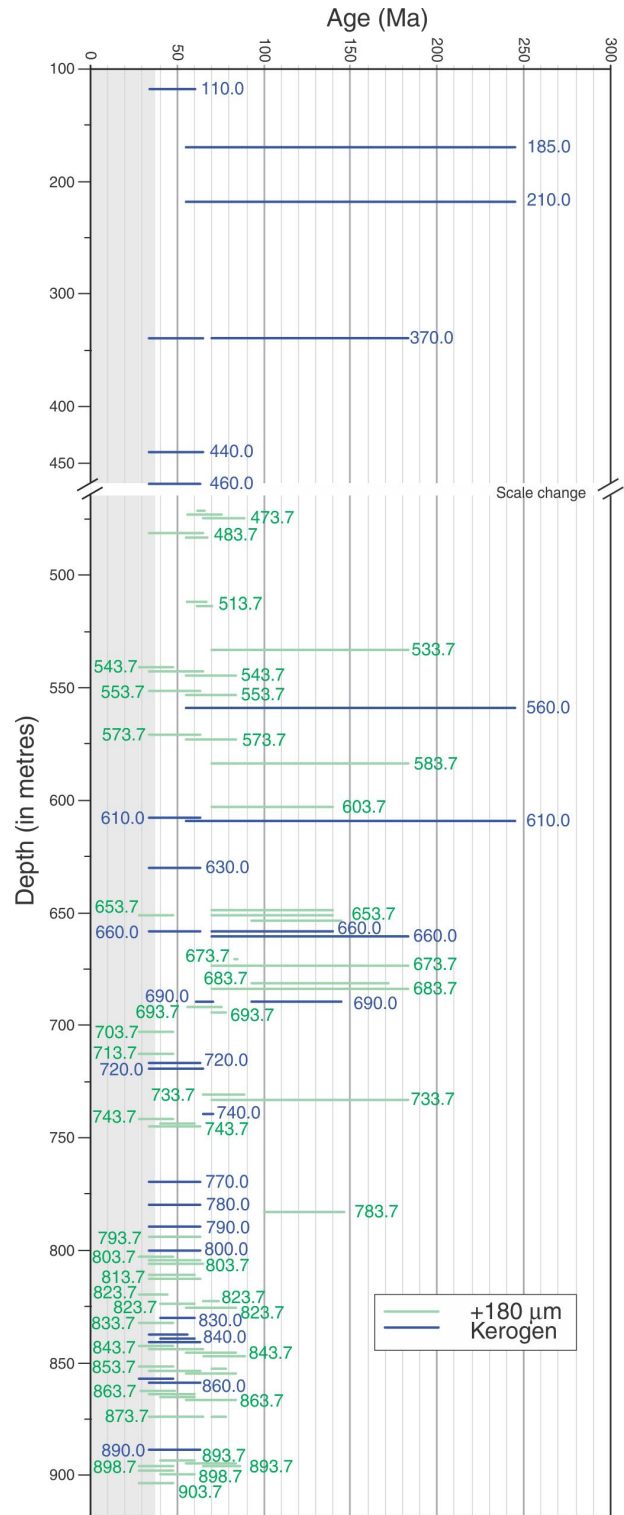


Figure 7. The age ranges of selected taxa considered likely to be recycled, for which one can provide reasonably certain age constraints, and their occurrence in the cuttings samples, 105 m to 900 m. More than one taxon may be plotted per sample. A coloured box indicates the estimated age range of the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

Between 650 m and 730 m, chiefly in the +180 μm fraction, occur several long-ranging Cretaceous taxa, including *Distaltriangulispores* spp., *Vitreispores* *pallidus*, *Appendicispores* sp., and *Tigrispores* sp. In this interval also occur the dinoflagellates *Chatangiella ditissima* (623.66 m and 653.66 m) and *C. verrucosa* (633.66 m). *Chatangiella ditissima* is of late Cenomanian to Campanian age in the Beaufort-Mackenzie Basin 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 650–680 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 paleodrainage 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 likely derived from the Tent Island and Smoking Hills formations exposed intermittently along the Yukon Coastal Plain and the middle reaches of the East Channel of the Mackenzie River (Norris, 1984; Lane and Dietrich, 1996).

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/gram 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 nonrandom 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. The coherent pattern of palynomorph concentration in the 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/gram of sediment can be calculated only for the clastic portion of the sediment from which palynomorphs could be released without oxidation (Fig. 8) because the exotic spike *Lycopodium* was retained in this kerogen fraction (*see* 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 m 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 downhole, at 570 m it was decided to acetolyze the remaining kerogen residues and mount new slides; this procedure was later extended to samples 550 m and 560 m.

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

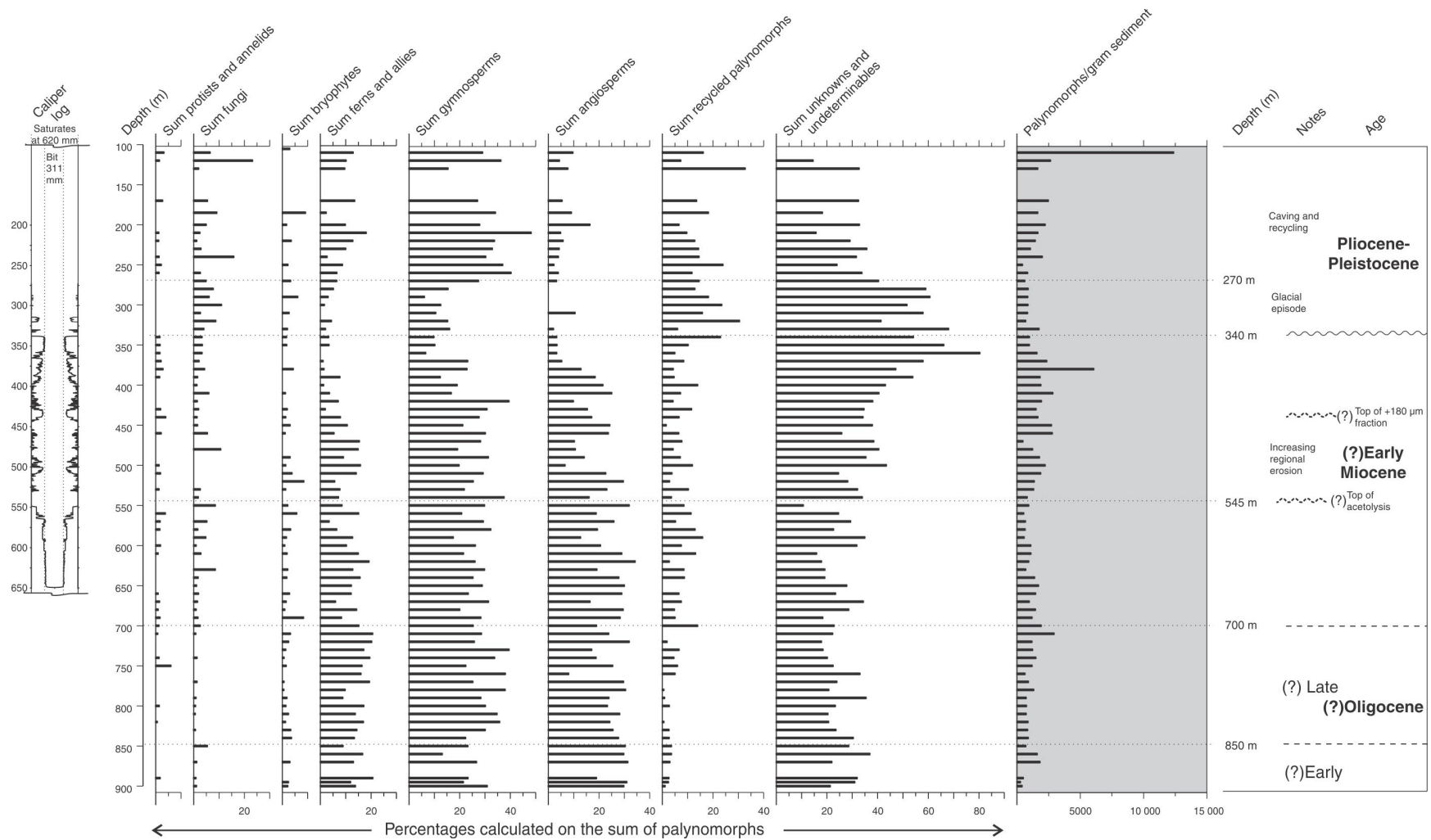


Figure 8. Percentages of groups of palynomorphs in cutting kerogen samples, calculated on the sum of palynomorphs, and concentration of palynomorphs/gram of sediment for 105–900 m, plotted with caliper log.

1. Acetolysis increased the palynomorph count by about 50% to about 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 versus 12 at 580 m, 18 versus 15 at 590 m, and 25 versus 12 at 600 m.
3. The Pinaceae/ Taxodiaceae-Cupressaceae-Taxaceae (including *Inaperturosporites dubius* as a Taxodiaceae-Cupressaceae-Taxaceae) ratio is very different at 580 m (1:4 for kerogen versus 1:1 for acetolysis) and 600 m (1:1 for kerogen versus 3:1 for acetolysis), but is similar at 590 m (6:4 for acetolysis versus 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 tricolpates was facilitated by the removal of micrometre-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 (Fig. 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 (Fig. 9 oversized) 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' (Fig. 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 (Fig. 2, 8). The interval from 116 m 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 320–560 m as having considerable erosion with some noneroded 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 m to 570 m is decline. The interval from 560 m to 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 Mallik 5L-38 well (White, 2009, Fig. 6). The Mallik 5L-38 analysis overlaps the interval from 670 m to 886.3 m that was studied in Mallik 2L-38. The concentrations for this interval in Mallik 2L-38 are in the range of 1000–1100 grains/g sediment, in good agreement with the estimates for Mallik 5L-38 ranging around 800–1200 grains/g sediment. Some of the minor trends are different in Mallik 2L-38, particularly the slightly higher values, between 1200 grains/g 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 Mallik 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 Mallik 2L-38 and Mallik 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 (Fig. 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, by taxonomic identification or by high thermal maturity, to be recycled. 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 (Fig. 2, 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 m 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. Stratigraphically upward, a stepped increase begins at 550 m, and a rising trend begins about 450 m, increasing to a broad peak between 380 m 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 substantially 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 m 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 m 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 250–200 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 m 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 cannot now 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 m 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 m 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 Mallik 5L-38 well 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 well samples

Studies of both the Mallik 2L-38 and Mallik 5L-38 wells are quantitative, and to a large degree the data are on an equal footing; nonetheless, 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 that carries many recycled palynomorphs. It was argued to be unlikely that palynomorphs typical of that fraction were released into pollen preparations for the Mallik 2L-38 well, in spite of the use of ultrasonic screening, light sodium hypochlorite 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 (*see below*).

Problems in correlation between Mallik wells 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 that 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 that are separable in a higher sedimentation rate environment, the sampling interval being equal.

Quantitative versus presence-absence records

In comparison between quantitative data and presence or 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 or absence record will approximate the underlying distribution to the degree that the area of maximum abundance, i.e. 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 or absence or quantitative analysis, although the latter is superior. The underlying distribution curve is asymptotic, so on statistical grounds one cannot 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. Despite this, there is a useful consistency of first appearance and last appearance datums in the geological record, where the sampling interval may be in the order of thousands or tens of thousands of years.

Rate of environmental change and definition of intervals

The rate of environmental change determines the shape of the distribution curve. Given continuous sedimentation, sudden truncations may indicate a rapid environmental change, or a gradual change reaching a critical environmental threshold for a taxon; however, 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 in hindsight may show to have not been appropriate. Zonations made by various workers can result from differing intuitive weighting of data, which may be rationalized by transition to numerical clustering techniques.

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

Patterns derived from Mallik wells should be verified by results from other Beaufort-Mackenzie Basin wells, but one must be mindful of problems in such comparisons. Mallik 5L-38 well has a 5 m cutting sample interval and 10 m analysis interval, versus the typical 30 m industrial cutting sample and analysis interval. Moreover, this study's research objectives required quantitative data versus the semiquantitative or presence or 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 versus 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 the Nuktak C-22 well, Norris (1986) noted that samples were macerated using standard oxidation at the Institute of Sedimentary and Petroleum Geology (I.S.P.G. now GSC Calgary). An

unpublished manuscript on laboratory palynology procedures by H. Johnson written in the 1970s does not indicate that preliminary screen removal of a coarse fraction was a standard procedure for the I.S.P.G. Palynology Laboratory at that time. R. Kalgutkar, who began working in the I.S.P.G. Palynology Laboratory in 1980, indicated that a +150 µm screening was standard procedure after oxidation (pers. comm., 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 well sample slides were processed in 1979.

Adgo F-28 well 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 the Nuktak C-22 well likely applies to Adgo F-28 well.

The 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 Basin 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 sediments in the Mallik wells are fluvial and deltaic in origin, 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 the Adgo F-28 well

In the Adgo F-28 well, 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 ft and 3000 ft (853.4 m and 914.4 m). If there is an erosional event at 2700 ft (823 m), it would suggest that it is the lower portion of the Kugmallit Formation that is represented. Recognition of this unit transfers many palynostratigraphic last appearance datums (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*, *Retiriletetes* 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 Sequence–Kugmallit Formation (Norris, 1997; McNeil *in White*, 2009). ‘*Integricorpus* sp. A’ is also found in Mallik

2L-38 well at 936.32 m, 946.21 m, 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 Parsons’ (2000) usage in her Caribou Hills study. ‘*Integricorpus* sp. A’ nominally occurs in Nuktak C-22 well (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 the Nuktak C-22 well.)

Tsuga and *Baculatisporites* are common in the upper Kugmallit Formation (the Arnak Member), in the lower Mackenzie Bay Formation in Nuktak C-22 well (Norris, 1986), and in the Mackenzie Bay in Adgo F-28 well (Norris, 1997). The recognition of the Kugmallit Formation in the Adgo F-27 well (McNeil *in White*, 2009) improves correlation between these two wells by putting some of the portion of most regular occurrence of their range into the Kugmallit Formation, 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 (1111 m) thick Kugmallit Formation section (Oligocene, 6920–3275 ft, 2109.2–998.2 m) overlain by a thinner, 1457 ft (444 m) Mackenzie Bay Formation section (Miocene, 3275–1818 ft, 998.2–554.1 m; Dixon, 1990). The Kugmallit Formation is divided into the lower Ivik and upper Arnak members. Comparatively, Adgo F-28 well has a thin, 200 ft (61 m) Kugmallit Formation section (3000–2800 ft, 914.4–853.4 m) and a 1100 ft (335 m) thick Mackenzie Bay Formation section (2800–1700 ft, 853.4–518.2 m) of similar thickness to the Nuktak C-22 well. The 200 foot (61 m) thick Kugmallit Formation 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 3399–3000 ft (1036–853.4 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 Formation.

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 wells. 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 formations. Taxa in bold face are those that occur in both wells near this boundary. Fungal hyphae type G is distinct, but *Tricolpites hians* is less so, and neither were recorded in the Mallik 2L- and Mallik 5L-38 well studies. *Dyadosporites oblongatus*

and *Dyadosporites* sp. A Norris are closely related and are called *Dicellaesporites* in this Mallik 5L-38 well study, where it is broadly distributed. *Intratropollenites crassipites* and *I. minimus* are closely related and are called *Tilia*-type herein. *I. crassipites* has a LAD higher in the Mackenzie Bay Sequence in Adgo F-28 well. A total of 40 taxa have LADS within 200 ft (61 m) of the boundary

Table 7. Taxa having a LAD within 200 ft above and below the Kugmallit–Mackenzie Bay formation boundary in Nuktak C-22 well (Norris, 1986) and Adgo F-28 well (Norris, 1997; McNeil *in* White, 2009). Taxa are spelled and are listed in the same order as in the relevant stratigraphic range chart. 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 formation boundary	Nuktak C-22	Adgo F-28
100–200 ft above (30.5–61.0 m)	<i>Intratropollenites crassipites</i> <i>Cupuliferoipollenites oviformis</i> <i>Dicellaesporites popovii</i> <i>Ostryoipollenites</i> sp. cf. <i>O. rhenanus</i> <i>Sparganiaceapollenites neogenicus</i>	<i>Echinatisporis</i> sp. A Norris
0–100 ft above (0–30.5 m)	<i>Annutriporites tripollenites</i> <i>Dyadosporites oblongatus</i> <i>Biretisporites potoniaei</i> Del. & Spr. Fungal hyphae type G <i>Staphlosporites delumbus</i> <i>Baculatisporites quintus</i>	<i>Hypoxylonites pirozynskioides</i> Eslik <i>Juglanspollenites verus</i> Raatz Fungal hyphae type G Norris <i>Multicellaesporites compactilis</i> Ke et Shi ex Sung et al. <i>Dyadosporites</i> sp. A Norris <i>Ericipites antecursoroides</i> Norris <i>Piceapollenites</i> sp. A Norris <i>Sequoiapollenites polyformosus</i> Thiergart
Mackenzie Bay Fm Kugmallit Fm 0–100 ft below (0–30.5 m)		<i>Momipites wyomingensis</i> Nichols and Ott <i>Caryapollenites inelegans</i> Nichols and Ott <i>Aceripollenites tener</i> (Samoilovitch) Norris <i>Multicellaesporites margaritus</i> Ke et Shi ex Sung et al. <i>Monoporisporites</i> sp. cf. <i>M. cupuliformis</i> Sheffy and Dilcher <i>Montanapollis globosiporus</i> (Samoilovitch) Srivastava <i>Integricorpus</i> sp. A Norris <i>Verrucatosporites favus</i> (Potonie) Thompson and Pflug <i>Retitriletes</i> cf. <i>R. novomexicanus</i> (Anderson) Norris <i>Intratropollenites minimus</i> Mai <i>Cupuliferoideaepollenites pusillus</i> (Potonie) Potonie <i>Tricolpites hians</i> Stanley
100–200 ft below (30.5–61.0 m)	<i>Pinuspollenites labdacus</i> <i>Tricolpites hians</i> Stanley <i>Reduviasporonites anangus</i> <i>Quercoidites microhenrica</i> <i>Ulmoideipites tricostatus</i> <i>Reduviasporonites</i> sp. A <i>Striacolporites</i> sp. A	<i>Momipites waltmanensis</i> Nichols and Ott <i>Pluricellaesporites</i> cf. <i>conspicuus</i> (Ke et Shi) Norris <i>Caryapollenites veripites</i> (Wilson and Webster) Nichols and Ott

in Nuktak C-22 and Adgo F-27 wells, 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 wells

Stratigraphic tops (or LADs) are nominally discrete events, but they are prone to statistical variability. Moreover, any taxon that 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 Basin 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 multimodal distributions). In the Nuktak C-22 well samples (Norris, 1986), several taxa occur regularly in the Arnak Member, but range upward into the lower Mackenzie Bay Member, including *Ulmipollenites undulosus*, *Baculatisporites crassiprimarius*, *B. quintus*, *Tsugaepollenites viridifluminiipites*, 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 850–700 m interval in Mallik 5L-38 well (excepting *Ulmus*-type, which is more intermittent) and suggest that interval to be late Oligocene, with more intermittent occurrences in the 700–550 m interval, thought to be Early Miocene. 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 10, the

palynological correlation of Late Eocene and younger strata in Mallik 5L-38 and Mallik 2L-38 wells to Beaufort-Mackenzie Basin wells and sections.

Interval 0–270 m

Although less so than the underlying stratigraphic interval, the 0–270 m interval has abundant recycled and unknown and undeterminable palynomorphs, but can still provide useful information. *Artemisia* occurs at 270 m and 260 m, and Onagraceae pollen at 220 m. The pollen and spore assemblage is low in abundance and diversity, consistent with a cool to cold environment. *Shepherdia*-type occurs at 105–110 m. Modern *S. canadensis* is a nitrogen fixer that can thrive on nutrient-poor mineral soils (Walkup, 1991) and is common in cool northern and montane environments; however, a possible extinct late Tertiary species may have grown on boggy soils (Matthews and Fyles, 2000). The percentage of *Picea*, a cool climate tree, is on average higher than in underlying intervals. The continued presence of Taxodiaceae-Cupressaceae-Taxaceae and *Inaperturosporites dubius* (probably Taxodiaceae-Cupressaceae-Taxaceae 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 Taxodiaceae-Cupressaceae-Taxaceae category.

Artemisia is the most distinctive marker in the Mallik 5L-38 well in the 0–270 m interval. *Artemisia*, and the apparent low diversity and abundance of vegetation, are consistent with a late Pliocene-Pleistocene age of 2.7 Ma or younger, after the onset of major northern hemisphere glaciation (White et al., 1999; Balco et al., 2005).

In Mallik 2L-28 well, core was recovered and analyzed from the 110 m 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 Mallik 5L-38 well (see below).

There is no direct palynological basis for correlation of the 0–270 m interval to the Nuktak C-22 well, 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 the Adgo F-28 well (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 (Fig. 8), palynomorph sum, and count sum of terrestrial palynomorphs are very low (Fig. 9), in spite of intensive slide scanning, so that percentage calculations have wide confidence limits. Nonetheless, there are significant features in this interval. *Alnus* and *Betula* pollen are generally absent, whereas *Pinus*, *Picea*, and Pinaceae undifferentiated are uncommon, in spite of the fact that these taxa are both long ranging and among the most common palynomorphs in the Neogene or Quaternary in northern Canada. *Sphagnum* is relatively abundant, suggesting that it was a common vegetative cover. Fungal hyphae and *Papulosporonites* occur consistently and in peak values. Of the sum palynomorphs, recycled palynomorphs comprise 5–30%, and unknowns and undeterminables comprise 40–80% (Fig. 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 that are likely in place. The caliper log (Fig. 2) shows that the hole is caved beyond the span of the logging tool, but there are resistant intervals at about 315–320 m, and from about 335–360 m, in which interval the hole is at gauge. *Cornus* and Chenopodiineae occur at 310 m. Chenopodiineae are common Neogene and/or Quaternary shrub and herb taxa, consistent with the interpretation of a harsh environment. The Chenopodiineae include 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 notable 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 cannot be correlated with nonquantitative studies. It likely correlates to the same published zones as the 0–270 m interval (*see above*).

There are no stratigraphically restricted taxa in this interval that provide correlation or age evidence (Fig. 10). Chenopodiineae is longer ranging in the Cenozoic. *Chenopodipollis* sp. A, equivalent to the term Chenopodiineae used here, occurs in the Nuktak C-22 well (Norris, 1986) once at 5100–5200 ft (1554.8–1585 m) in the uppermost Ivik Member, and is somewhat more common between 2900 ft and 1200 ft (884 m and 365.8 m) in the Mackenzie Bay and lower Nuktak formations; hence its range in the Nuktak C-22 well precludes precise correlation. In the Adgo F-28 well, Norris (1997) 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 the Adgo F-28 well.

Deposition of eroded material was a dominant process in the strata between about 270 m and 340 m. An explanation for erosion could be tectonism, but the proximity to the modern surface suggests that the cause was mid- to late Pliocene-Pleistocene glaciation (White et al., 1999; Duk-Rodkin et al., 2010; Duk-Rodkin and Barendregt, 2011; Gao et al., 2012). 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 well at 346 m, based on log interpretation. This coincides remarkably with this palynological zonation of Mallik 5L-38 well.

Gas zonation

There is a correlation between the palynological zonation in Mallik 5L-38 well and gas zones of Lorenson et al. (2005), where the 0–350 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.

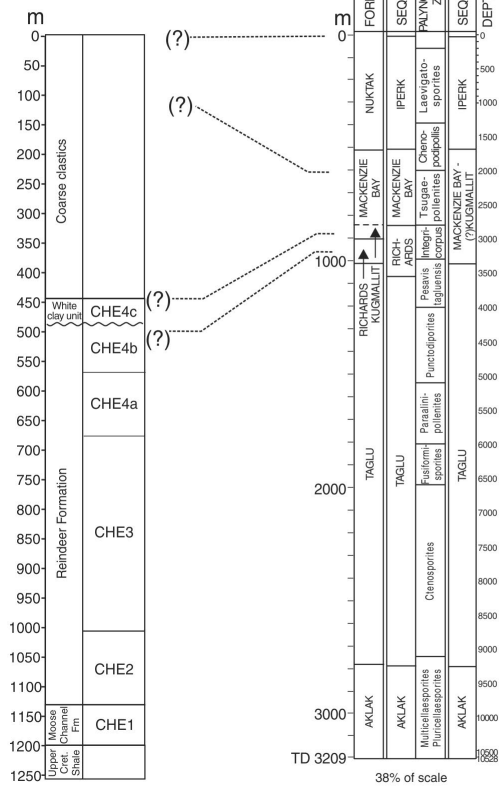
The upper boundary of this interval, 340 m, is in the interval of peak abundance of the sum of unknown and undeterminable palynomorphs, declines in the sums of angiosperms and in abundance or regular occurrence of *Alnus*, *Betula*, and Ericales. It is near the base of an interval of very low concentration of palynomorphs (Fig. 8, 9).

Adgo F-28

(Norris, 1997; McNeil in White, 2009)

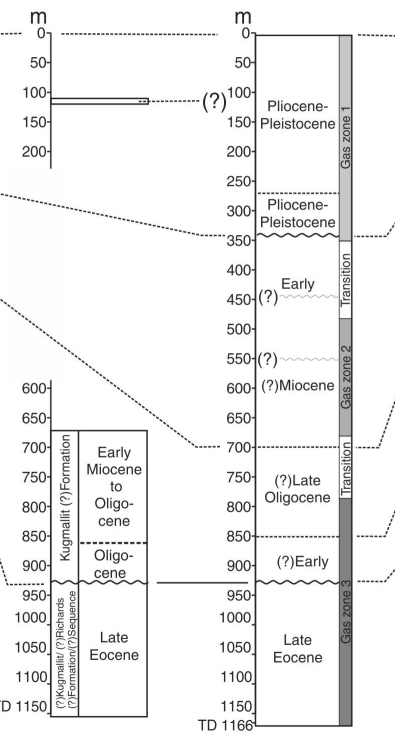
Caribou Hills

(Doerenkamp et al., 1976; Parsons, 2000)



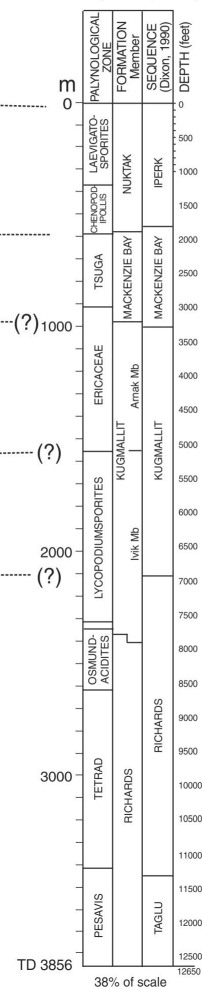
Mallik 2L-38 Mallik 5L-38

(White, 2009) (this report; Lorenson et al., 2005)



Nuktak C-22

(Norris, 1986)



Ukalerk C 50

(McNeil et al., 1982; Dixon, 1990)

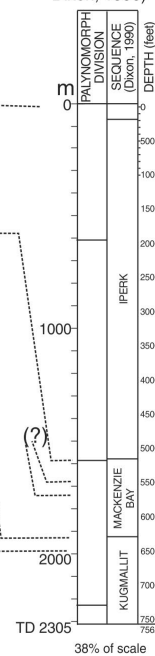


Figure 10. Palynological correlation of Late Eocene and younger strata in Mallik 5L-38 and Mallik 2L-38 wells to Beaufort-Mackenzie Basin wells and sections discussed in the text. For correlation of older strata, see the references indicated. Cret. = Cretaceous

At the base of this interval, 700 m, there is no identified lithostratigraphic change, and it is defined primarily by changes in the percentages of ferns and fern allies. It is the top of the regular occurrence of *Baculatisporites crassiprimarius*, *Baculatisporites quintus*, and *Baculatisporites* sp. (which occur sporadically up to 610 m). *Laevigatosporites* declines in percentage abundance, the sum fungi increases, and *Larix* and/or *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 340–700 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 Taxodiaceae–Cupressaceae–Taxaceae pollen, in palynomorphs per gram 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 well, but occurs in adjacent strata at 690 m, 860 m, 890.71 m, and 900.63 m in Mallik 2L-38 well). *Tsuga* spp. occur rarely above this point. Within this 700–550 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 Taxodiaceae–Cupressaceae–Taxaceae pollen) and a further increase in the concentration of palynomorphs per gram sediment. This likely also represents accelerated regional erosion.

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

By the constraint of the super- and subjacent strata, this interval could fall in the age range of Miocene to perhaps Early Pliocene (Fig. 10). 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 well (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 well, is also evinced

in Ukalerk C-50 well at 6300–6500 ft (1920–1981 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 well at 5500–5700 ft (1676–1737 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 the Mallik 5L-38 well, 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 et 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 Northwest Territories, Yukon, and Alaska. A tempting correlation of the occurrence of *Tsuga* and *Tsuga canadensis*-type in Mallik 5L-38 well, 570–900 m interval, to the late Miocene–early Pliocene resurgence of *Tsuga* spp., seen in Usibelli Group L2 and G zones (*see* below), is not accepted here. The abundant presence of Taxodiaceae–Cupressaceae–Taxaceae 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-existent 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 5–10%, 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 late Late Miocene upper Lignite Creek Formation, Zone G, and late Miocene–early Early Pliocene Grubstake Formation, Zone G (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 ± 0.02 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 less than 1% in the Pliocene terrace gravels at Circle, Alaska. *Tsuga* sp. is not recorded in the probably early Pliocene Lower White Channel Gravel deposits at Jackson Hill, Yukon 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 Pleiocene-Pleistocene core samples in Mallik 2L-38 well (White, 2009).

In the Ukalerk C-50 well in the Beaufort Sea (Fig. 10), *Tsugaepollenites* spp. is recorded by presence or 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 Early Pliocene (McNeil et al., 1982; Dixon, 1990). The Late Miocene Akpak Sequence is missing between the Mackenzie Bay and the Iperk Sequences in Ukalerk C-50 well (Dixon, 1990; McNeil et al., 2001) due to the unconformity underlying the Iperk Sequence (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 ft and 3300 ft (1127.8 m and 1005.8 m), 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 Pliocene-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 the Adgo F-28 well, 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 the Nuktak C-22 well, 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 wells, 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 well 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 wells, a minimum mid-Miocene age could 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 Formation (S-2 and S3A, B) assemblages host a thermophile-rich late Early to Middle Miocene palynomorph assemblage, also documented in the 15.2 Ma Upper Ramparts site (White and Ager, 1994). This thermophile-rich assemblage is not in evidence in Mallik 5L-38 well below the *Tsuga* tops. Hence, whereas 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 m to 700 m strata. Unfortunately, the palynology of the Early Miocene in the Beaufort-Mackenzie Basin is poorly known.

In Mallik 5L-38 well, *Baculatisporites* spp. has 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 ft and 3199 ft (701 m and 975.1 m) in Nuktak C-22 well (Norris, 1986), and between 1900 ft and 2100 ft (579.1 m and 640.1 m) in Adgo F-28 well, also the middle of the 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 (Fig. 10). If the Early Miocene age interpretation for this interval is correct, it implies a significant unconformity near 340 m with Early Miocene overlain by Pliocene-Pleistocene sediment, and with the Middle and Late Miocene and (?)Early Pliocene missing. The changes at 445 m 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 well record is consistent with the erosional unconformity under the Iperk Sequence 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 Pliocene-Pleistocene glaciation, was probably removed by the erosion that developed the unconformity under the Iperk Sequence or by subsequent glaciations.

Lane and Dietrich (1995) argued for a late Miocene tectonic pulse, but if the Early Miocene age interpretation of the 340–700 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 the Adgo F-28 well, 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 the Ukalerk C-50 well. 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 Mallik 5L-38 well into gas zone 1 (0–350 m) that has microbial gas, and gas zone 2 (470–680 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 m 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 rare taxa (Fig. 8, 9).

Ericales' interval of most regular occurrence is from 700 m to 850 m; below and above this interval they are more sporadic, although sometimes more abundant. *Baculatisporites quintus* and *Baculatisporites crassiprimarius* occur regularly between 710 m and 850 m and were not found in the samples below 850 m in Mallik 5L-38 well. *Tsuga canadensis*-type, with *Tsuga* sp., occur more regularly than elsewhere in the well between 730 m 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 m 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 (Fig. 10). Nonetheless, there are patterns of regular and intermittent occurrence in those wells that suggest arguments for correlation with the Mallik 5L-38 well, 700–850 m interval. In Nuktak C-22 well, *Baculatisporites crassiprimarius* ranges from the basal Richards Formation into the middle of the 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 well, *Baculatisporites crassiprimarius* occurs in the mid- to lower Mackenzie Bay and in the Taglu formations, and *B. quintus* is sporadic in the mid- and lower Mackenzie Bay Formation. *Tsugaepollenites viridifluminipites*, in Nuktak C-22 well, occurs up to the middle of the 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 Formation taxon. The Eriopites zone, Norris (1986) noted, is nearly co-extensive with the Nuktak C-22 well Arnak Member, but occurrences of *Eriopites compactipollinatus* extend into the Mackenzie Bay Formation. Hence, these taxa between 700 m and 850 m in Mallik 5L-38 well 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 wells. The Eriopites Zone in Nuktak C-22 well is probably Late Oligocene and the *Tsugaepollenites* zone of the Mackenzie Bay Formation may be latest Oligocene or more probably Miocene (Norris, 1986). Detailed discussion of the Beaufort-Mackenzie Basin biostratigraphic framework is found in more recent literature (McNeil, 1997; Norris, 1997).

In Mallik 5L-38 well, *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 the Ukalerk C-50 well (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 well, 700–830 m interval.

The Oligocene was a time of dynamic climate change from 'greenhouse' to 'icehouse'. High resolution of Oligocene paleoclimatic cycles is provided by marine isotopic studies, indicating a rapid onset of early Oligocene Antarctic glaciation, driven by astronomical forcing and

atmospheric CO₂ levels (DeConto and Pollard, 2003; Coxall et al., 2005; Pälike et al., 2006; DeConto et al., 2008). Oligocene climate cycles may have been mediated by effects of solar insolation on biosphere productivity. 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, with the coldest temperatures and/or largest Oligocene ice volumes ca. 26.8 Ma (Pälike et al., 2006). A climatic warm event is an aspect of the Late Oligocene and may figure in the interpretation of the Mallik 5L-38 well, 700–850 m interval. 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 Simaëys, 2004; Van Simaëys, 2004). The Arnak Member in the Beaufort-Mackenzie Basin (Norris, 1986) is Late Oligocene (Chattian) 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. McNeil (1990) indicated that the foraminifer genus *Nuttallides* in the Beaufort Sea indicates warm climate conditions. In the Mallik 5L-38 well 700–850 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 well interval 6300–6500 ft (1920–1981 m), which has an assemblage including *Pterocaryapollenites*, *Caryapollenites* spp., *Ilexpollentites*, and the “*Tiliaepollenites* - *Bombacacidites* complex” (McNeil et al., 1982); however, the evidence for Late Oligocene, Chattian, climatic warmth is not abundant in the Mallik 5L-38 well, possibly a result of relatively low palynomorph counts.

The interval in the Mallik 5L-38 well from 830 m to 900 m with minimal *Tsuga* spp. and from 850 m 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, 1982, 1986). There is a decline in the count sum of terrestrial palynomorphs (Fig. 9) and in the palynomorph concentration (Fig. 8) 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 the stratigraphic patterns of which are episodic, for example, *Triatriopollenites granilabratus* (Stanley) Norton in Norton and Hall 1969. *Triatriopollenites granilabratus* occurs in Mallik 5L-38 well at 830 m and 840 m. It is illustrated from the Caribou Hills by Parsons (2000, Pl. 9, fig. 31–33, 39) and is found in Late Paleocene and Early to Middle Eocene CHE 1 to CHE4b. Morphologically, *T. granilabratus*

compares favourably with *Ostryoiipollenites* sp. cf. *O. rhenanus* (Thompson) Potonié ex Potonié 1960 in Nuktak C-22 well. There, *Ostryoiipollenites* sp. cf. *O. rhenanus* is found stratigraphically in the lowermost Mackenzie Bay and Arnak equivalent interval, 3000–4700 ft (914.4–1432.6 m) (Norris, 1986, Pl. 10, fig. 35–37), although in Nuktak C-22 well it is not found in the Richards or Taglu formations. The presence of this taxon in Mallik 5L-38 and Nuktak C-22 wells, 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 occurred in the late Oligocene (De Man and Van Simaëys, 2004).

Gas zonation

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

Unconformity or disconformity near 930 m

The Oligocene Antarctic glaciation caused sea-level lowering of at least about 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 well (Jenner et al., 1999) and Medioli et al. (2005) identified a “significant” boundary at 932.6 m in Mallik 5L-38 well (Fig. 10). White (1999) suggested that this approximated the Eocene-Oligocene boundary. The Oi-1 glaciation followed the Eocene-Oligocene boundary by about 800 ka (De Conto and Pollard, 2003), but it likely formed an erosional disconformity identified in the Mallik wells, with an undetermined loss of sedimentary record.

In the Beaufort-Mackenzie Basin, Lower Oligocene submarine fans in the vicinity of the Kopanor oil field represent lowstand deposits, and there is an equivalent deposit on the Labrador Shelf (Harrison et al., 1999). On the Scotian Margin, canyon incision began at the shelf edge in the Eocene, but in the Oligocene there was extensive canyon incision and a significant Oligocene unconformity in many wells; in others, that penetrate an Oligocene Canyon, there is an Oligocene section (Fensome et al., 2008). The Scotian Margin geological context is different from the Mackenzie Delta in that the Scotian Shelf is part of a passive margin, whereas the Mallik wells are in a tectonically active regime with adjacent fluvial sediment supply. The degree of expression of an unconformity in the Mallik context would depend on sea-level change, the rate of sediment supply, and fault-block subsidence.

Interpretation of paleoclimatic proxy ratios

The analysis of Mallik 5L-38 well complements that of Mallik 2L-38 well and fills in the biostratigraphic information for the strata above 670 m. By research design, the study interval in the Mallik 5L-38 well overlaps the 900 m to 660 m interval in the Mallik 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 (*see above*), but the pollen ratios show differences that require consideration. The Mallik 5L-38 ratios were calculated using the same taxa reported in Mallik 2L-38 well, although the thermophilous angiosperm assemblage in Mallik 5L-38 well is impoverished compared to Mallik 2L-38 well.

Figure 11 shows the pollen ratios from Mallik 2L-38 well (White, 2009) and Mallik 5L-38 well that serve as experimental proxies for paleotemperature. All ratio series have been minimally smoothed with a three-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 Basin since Staplin (1976). First, the ratio curves for Mallik 2L-38 well 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 give confidence that the ratios reflect real vegetation events, even though those simultaneous peaks were probably driven by short-term edaphic conditions affecting *Pinus* and *Ulmus*. Two ratios, Taxodiaceae-Cupressaceae-Taxaceae /total Pinaceae and (temperate angiosperms)–*Ulmus*/total angiosperms, are more stable proxies for climatic temperature. From 1150 m to about 890 m these two ratios follow a general declining trend with joint peaks around 1110 m, and another muted offset peak around 1050 m 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 culminated in the early Oligocene cold event; however, in the 890 m to 670 m interval of Mallik 2L-38 well the ratios are no longer in phase. Moreover, a more detailed comparison of the patterns in the overlapping section of the Mallik 2L-38 and Mallik 5L-38 wells, and in the different ratios within the Mallik 5L-38 well, reveals dissimilarities. Those discordant patterns may be due to vegetation reorganization, 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)–*Ulmus*/total angiosperms. In the Mallik 2L-38

well *Ulmus*-type pollen is a significant fraction of the temperate angiosperm pollen. In Mallik 5L-38 well, *Ulmus*-type is a relatively small and sporadic component of the angiosperms (Fig. 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 m and 700 m in the interval that is interpreted as probably representing a warm Chattian Age (*see above*). What is unexpected, considering previous discussions, is the gap in values between 800 m and 760 m.

In Mallik 2L-38 well (White, 2009), the ratios used for paleotemperature interpretation for the section below about 890 m were the Taxodiaceae-Cupressaceae-Taxaceae / Pinaceae and (thermophilous angiosperms)–*Ulmus*/total angiosperms. In Mallik 5L-38 well 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 m and 650 m, with a subsequent rising trend. Angiosperm ratios of temperate taxa to all angiosperms is lower in Mallik 5L-38 well than in Mallik 2L-38 well in the overlapping 900–660 m section and the ratios are not in phase; however, what is similar between the two wells is the relatively low values in the 900–850 m interval with increase in overlying section to 800 m.

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

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

In summary, Figure 11 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 Mallik 2L-38 well than Mallik 5L-38 well, excepting the *Pinus/Picea* ratio. There are higher values of temperate angiosperms/total angiosperms for Mallik 2L-38 well compared with Mallik 5L-38 well. 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 Mallik 2L-38 and Mallik 5L-38 wells, within a hundred metres of one another, to have comparable patterns. Nonetheless, in the Mallik 5L-38 ratios (Fig. 11), a

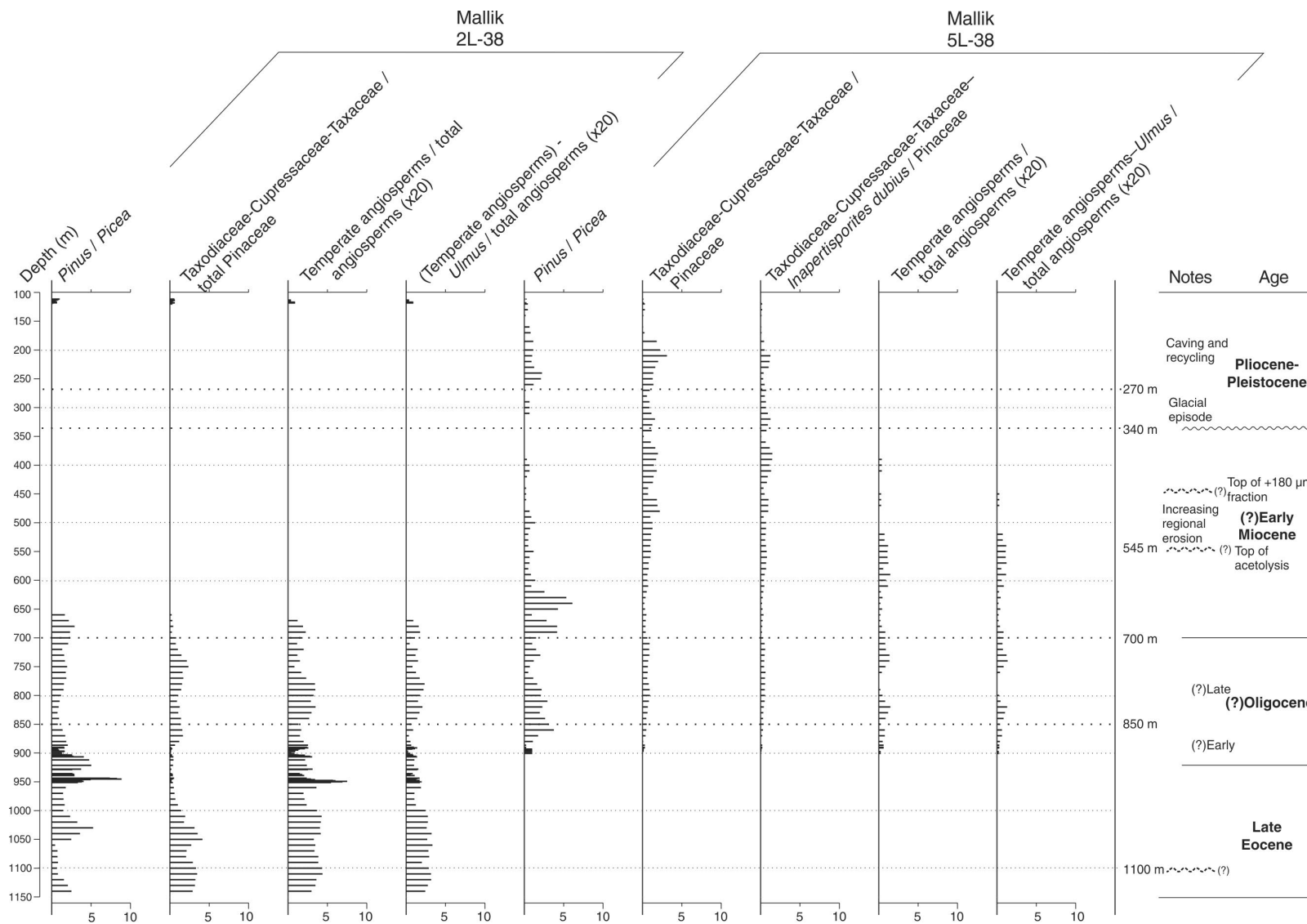


Figure 11. Ratios of selected pollen taxa in Mallik 2L-38 and 5L-38 wells. The ratios for Mallik 5L-38 well are calculated following the parameters explained in White (2009) and have been smoothed with a three-point moving average. The two wells have been interfiled by depth of sample. Between 870 m and 900 m, the wells have samples at different intervals. Where 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 Mallik 5L-38 by reducing the values, at 870 m, 890 m, 895 m, and 900 m. This does not fundamentally affect the interpretation. Values of temperate angiosperms/total angiosperms, and (temperate angiosperms)-*Ulmus*/total angiosperms are multiplied x20 for visibility.

common feature of the 900–800 m interval is a rising trend implying climatic warming, a pattern which generally matches that found in the Mallik 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 Mallik 2L-38 and Mallik 5L-38 wells is supported by a fence diagram of gas-hydrate saturation (Dallimore and Collett, 2005b, their Fig. 6) and by magnetotelluric log (Craven, 2007) assessment of gas-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 11.

Modifications of processing in Mallik 5L-38 well 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 well (White, 2009), corroborated by this study of Mallik 5L-38 well (Fig. 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 at about 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 well 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 COAL SAMPLES FROM CORE, 933–1151 m

The Mallik 5L-38 well was cored from 885 m 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 m and 1081.90 m. By simple depth correlation to Mallik 2L-38 well, 100 m to the northeast (above), these samples fall within the strata interpreted to be Late Eocene (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 four 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 cm to 3 cm thick beds and are plotted by their bottom depth (Fig. 12 oversized), 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 GSC Bulletin 585 (Dallimore and Collett, 2005a) 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 (Mueller-Dombois and Ellenberg, 1974). 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. (1999a, b, 2001) have been published. The interest here centres on the minimum warmth indicated by the thermophilous species. Temperature only is considered here because it is a prime environmental determinant of plant ranges, and is a Cenozoic climate parameter best known by marine $\delta^{18}\text{O}$ records (*see* discussion of the Oligocene, above). Moisture, edaphic conditions, and interspecies competition are other significant determinants of plant ranges. For moisture parameters, Thompson et al. (1999a, b, 2001) can be consulted.

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.

933.65–940.95 m

Assemblage and age

This assemblage comprises five samples in two closely spaced groups: 933.65 m, 933.93 m, and 934.21 m, underlain by 940.53 m and 940.95 m samples. *Alnus*, Ericales, *Laevigatosporites*, *Triporopollentites* and *Ulmus*-type, Taxodiaceae-Cupressaceae-Taxaceae, and Pinaceae are common to abundant.

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 Late Eocene (Long and Sweet, 1994). *Lonicerapollis gallwitzii* occurs in the sample, and in the Mackenzie Bay and upper Kugmallit formations in Adgo F-28 well (Norris, 1997; McNeil *in* White, 2009) and A.R. Sweet noted that it ranges down into the Eocene in northern Canada (pers. comm., 18 February 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 Late Eocene to possibly Early Oligocene strata (Ridgway et al., 1995).

The occurrence here of the new triprojectate pollen, *Striatocorpus sweetii* White 2009 (934.21 m) extends its stratigraphic range upward 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 *Mancicorpus* 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 (Fig. 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 based on pollen morphology, 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 μm /30 μm in polar/equatorial axes (respectively), another (a-13.9/11.0) is 20 μm /32 μm , and a faint infrareticulum is visible on this specimen. The specimen of *S. sweetii* at 934.21 m is 18 μm /28 μm and is shaped like the holotype (White, 2009, Pl. 5, fig. 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 μm /28 μm , and is more rhombic-shaped or isopolar with a faint infrareticulum. This shape matches

a specimen (White, 2009; Pl. 5, fig. 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 three-pored Ulmaceae grains, as Leopold and Liu (1994) indicate that *Zelkova* is three- and four-pored and *Ulmus* and *Planera* would generally be four- to six-pored (Lieux, 1980b). *Nyssa* is present and *Carya* and Poaceae pollen are questionably present.

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

In the Mallik 2L-38 well at 946.2 m, near the stratigraphic interval described here, Kurita and Uchida (1999) described a small Paleocene to Eocene dinoflagellate assemblage. They dismissed this assemblage as recycled, although the age is compatible with that derived from pollen and spores herein and in the Mallik 2L-38 well (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°C and 15°C, respectively (Table 8). Although *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 United States, 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

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

Mallik 5L-38 depth interval (m)	Fossil pollen type	Modern American relatives (Thompson et al., 1999a, b, 2001)	January minimum mean monthly temperature (°C)	July minimum mean monthly temperature (°C)
933.65–940.95 m	<i>Carya</i>	<i>Carya cordiformis</i>	-17	17
		<i>Carya ovata</i>	-13	17
	<i>Nyssa</i>	<i>Nyssa sylvatica</i>	-12	15
	<i>Quercus</i>	<i>Quercus</i> East	-23	13
	<i>Ulmus</i> -type	<i>Ulmus</i>	-23	13
		<i>Planera aquatica</i>	0	26
Range of temperature limits			-17 to -23	13 to 26
1005.18–1005.56 m	<i>Carya</i>	<i>Carya cordiformis</i>	-17	17
		<i>Carya ovata</i>	-13	17
	<i>Ilex</i> -type	<i>Nemopanthus collinus</i>	-4	17
		<i>Ilex verticillata</i>	-17	14
	<i>Juglans</i>	<i>Juglans</i> East	-15	15
	<i>Liquidambar</i>	<i>Liquidambar styraciflua</i>	-4	15
	<i>Nyssa</i>	<i>Nyssa sylvatica</i>	-12	15
	<i>Quercus</i>	<i>Quercus</i> East	-23	13
	<i>Ulmus</i> -type	<i>Ulmus</i>	-23	13
Range of temperature limits			-4 to -23	13 to 17
1043.16–1053.68 m	<i>Pachysandra</i> - <i>Sarcococca</i>	<i>Pachysandra procumbens</i> (by range of <i>Liriodendron tulipifera</i>)	-10	17
	<i>Juglans</i>	<i>Juglans</i> East	-15	15
	cf. <i>Liquidambar</i>	<i>Liquidambar styraciflua</i>	-4	15
Range of temperature limits			-15	17
1081.87–1081.90 m	<i>Magnolia</i> -type	<i>Magnolia acuminata</i>	-7	18
		<i>Magnolia virginiana</i>	-3	22
		<i>Magnolia tripetala</i>	-5	18
Range of temperature limits			-3 to -7	18 to 22

for January and July of -23°C and 13°C, respectively. *Carya* would require warmer winters and summers of -17°C and 17°C, respectively. The range of minimum mean monthly temperatures for January are -17°C to -23°C and for July and 13°C to 17°C (Table 8).

Paleoenvironment

The abundance of *Alnus*, Ericales, and *Laevigatosporites* together with some Pinaceae and Taxodiaceae-Cupressaceae-Taxaceae 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 well. It is suggested above that this boundary may be an unconformity associated with sea-level drawdown due to the Oi-1 Antarctic glaciation; however, the Mallik site was a zone of subsidence on a listric fault (Brent et al., 2005; White, 2009); the timing and rate of subsidence may affect the nature of the unconformity.

Haberer et al. (2005) identified organic matter in the Mallik 5L-38 well, 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 m to 1000 m in Mallik 5L-38 well, 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) described the sedimentology of the 926.5–952.2 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, but not their interpretation of recycling.

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, which show variations in morphology. *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 Taxodiaceae-Cupressaceae-Taxaceae pollen) and little Pinaceae pollen.

?*Brefeldiellites* sp. (1005.56 m) is an ostiolate sheet of poorly arranged fungal cells. Two species of *Brefeldiellites* from the Early Cretaceous and the Early Eocene have been described. 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 (United States Department of Agriculture, 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 m 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 (Pl. 4, fig. 11–14) occurs in Mallik 5L-38 well at 1005.18 m, 1005.38 m, 1005.41 m, and 1005.56 m. Fungal hyphae type D occurs sporadically in the Nuktak C-22 well in the Richards Formation and Ivik Member of the Kugmallit Formation, and has a last appearance datum in the overlying Arnak Member (Norris, 1986).

Lonicerapollis gallwitzii Krutzsch 1962 occurs in sample 1005.31 m, and its range is Eocene to Miocene (*see above*).

Paleoclimate

This group 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 high abundance in 1005.38 m); *Quercus* (1005.18 m, 1005.31 m, 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°C to -23°C, and for July of 13°C to 17°C (Table 8). There are many multicellular fungal sheets of (?)epiphyllous fungi, including ?*Brefeldiellites* sp., suggesting a humid climate.

Paleoenvironment

The abundance of Ericales pollen in this interval suggests an acidic wetland, but the near absence of commonly associated bryophyte spores such as *Sphagnum* suggest that the pH was likely above 4.5 to 5.5 (Vitt, 1994; Devonian Botanic Garden, 2013), suggesting flow of surface or ground water through the wetlands. The dominance of Ericales, with little upland coniferous pollen from the Taxodiaceae-Cupressaceae-Taxaceae or Pinaceae, has three conceivable explanations; a broad extent 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 common occurrence of fungi in the lower sample (especially Fungi hyphae, *Inapertisporites* sp., *Monoporisporites* sp.) and of *Nyssa* pollen (1005.38 m) suggests environmental development that may be a hydrosere succession from moist to inundated conditions, and may have to do with changing base levels controlled by climate, eustasy, or tectonics. In North America *Nyssa* commonly inhabits moist soils and swamplands in the southeastern temperate forests (Everett, 1969), ranging north to southernmost Ontario. *Nyssa sylvatica* likes moist acidic soils, but will grow on dryer, upland soils (Hosie, 1969; Farrar, 1995); 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) described the 1000–1070 m interval, encompassing this 1005.18–1005.56 m suite of samples and the 1043.16–1053.68 m 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, Taxodiaceae-Cupressaceae-Taxaceae and *Inapertisporites dubius* pollen. *Inapertisporites dubius* is probably a Taxodiaceae-Cupressaceae-Taxaceae pollen, being comparable to pollen of the bald cypress, *Taxodium* (Lieux, 1980a, Pl. VII, fig. 6), although papillae were not seen. There is considerable plant and fungal detritus.

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. *Boisduvalia clavatites* (1043.31 m) was described from the Late Eocene Australian Creek Formation of central British Columbia (Piel, 1971; Long and Sweet, 1994). Fungal hypha type D of Norris (at 1053.49 m) also is consistent with an Eocene age (above). *Jussiaea (Ludwigia)* sp. is Late Eocene (*see above*).

The distinctive pollen of *Pachysandra-Sarcococca* (1043.32 m and 1053.69 m) derives from the 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 m, 1053.68 m) occurs in one cuttings sample at 3800 ft (1295 m) in Adgo F-28 well in the uppermost Taglu Formation, virtually at the contact with the Richards Formation (Norris, 1997). Its occurrence here argues that it ranges upward 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) interpretation that the species *Alnus scotica* Simpson 1961 (p. 443) is similar to the modern pollen of *A. seiboldiana* of Japan. Parsons (2000) used *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.R. Sweet, pers. comm., 21 February 2007).

Paleoclimate

Pachysandra and *Sarcococca* are not included in Thompson et al. (1999a, b, 2001), but the distribution of *Pachysandra procumbens*, according to the Plants database (United States Department of Agriculture, 2007), is similar to *Liriodendron tulipifera*, for which Thompson et al. (1999a) provided climatic tolerances. This suggests a minimum mean monthly temperature for January and July of -10°C and 17°C, respectively, based only on the range of *L. tulipifera*. Gray and Sohma (1964) studied the pollen of *Pachysandra* and *Sarcococca* and also note that the modern Eurasian and American centres of *Pachysandra* and *Sarcococca* have a humid, moderate climate with warm summers of temperatures above 22°C (72°F) and mild to cool winters, seldom below freezing. Rain falls throughout the year, peaking in summer (Gray and Sohma, 1964). Hence, the temperature limits derived from *Liriodendron* may be low estimates. Schubert et al. (2012) interpreted a summer precipitation maximum for Arctic forests of the Eocene, based on $\delta^{13}\text{C}$ measurements of Early Eocene and undifferentiated Eocene wood; the pattern fits well with the modern *Pachysandra-Sarcococca* precipitation pattern, and must have provided moisture for energetic growth during long summer days.

Paleoenvironment

The assemblage is limited, but the reduced abundance of Ericales and greater abundance of Pinaceae and Taxodiaceae-Cupressaceae-Taxaceae pollen 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 Ericales pollen, but much less of that than in overlying assemblages. One specimen of *Magnolia* pollen occurs (see Lieux, 1980a, Pl. X, fig. 1–7).

?*Viburnum* sp. cf. *V. cassinoides* of McIntyre 1991 suggests an Late Eocene age (see 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. Here, it is much above the accepted stratigraphic range for *A. quadrilobus*. Tschudy and Leopold (1970) noted *A. quadrilobus* right up to Cretaceous-Tertiary boundary and Nichols and Sweet (1993) included it in the Maastrichtian *Wodehouseia spinata* assemblage. *Aquilapollenites quadrilobus* ranges into the Paleocene, but A.R. Sweet stated he has never seen a population of specimens that convinces him that it legitimately occurs in younger strata (A.R. Sweet, pers. comm, 16 March 2006). Nonetheless, if this specimen is recycled from the Late Cretaceous *Wodehouseia* assemblage, there is no evidence of the rest of that assemblage in the Mallik 5L-38 well, 1081.87–1081.90 m sample. This sample's microflora shows continuity in composition with adjacent assemblages. The *Aquilapollenites* sp. cf. *A. quadrilobus* presence here in a coal argues that it is not recycled and that instead, it ranges into the Late Eocene in certain favourable environments. Another occurrence of *A. quadrilobus* in the Mallik 2L-38 well (951.29 m) was considered to be recycled (White, 2009), perhaps incorrectly. The possible diachroneity of this specimen is troubling.

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°C to -7°C and for July of 18°C to 22°C; however, there are no other indicator taxa to support this interpretation.

Paleoenvironment

The abundance of ferns would seem to indicate a less paludal, acidic environment than indicated by the Ericales-rich samples above, although it was sufficiently inundated to

accumulate organic matter. Based on geochemical analysis, Chen et al. (2005) described the 1070–1150 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 analyzed are not from recycled, detrital coal. Biostatigraphic indicators such as *Boisduvalia clavatites*, *Jussiaea* (*Ludwigia*), *Mancicarpus* 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 the modern relatives of which 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) noted that the age separation between the latest Eocene Rex Creek and the probable Oligocene Angoonian megafloreal 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 about 15°C, whereas the small Angoonian assemblage yielded a mean annual temperature of about 4.5°C. By isotopic measurements of teeth and bone from mammal fossils, Zanazzi et al. (2007) estimated an $8.2 \pm 3.1^\circ\text{C}$ temperature drop in mid-continental North America across the Eocene-Oligocene transition. The paleoclimatic inference from the Mallik 5L-38 well coals is clearly consistent with an Eocene climate. The direction of temporal change of estimated paleotemperature in the Mallik coals trends toward 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 toward representation of the local wetland floras, which are apparently mostly heath (Ericales) dominated, with

ferns dominating the lowest sample. The upland floras of arboreal angiosperms, Taxodiaceae-Cupressaceae-Taxaceae, and Pinaceae are much less well represented.

The general absence of strong Taxodiaceae-Cupressaceae-Taxaceae 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 Taxodiaceae-Cupressaceae-Taxaceae 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 (United States Department of Agriculture, 2006). In contrast, samples from 933.65 m to 1005.56 m are dominated by the Ericales. A wetland Ericaceae such as *Ledum groenlandicum* can tolerate a pH of 5.0 (United States Department of Agriculture, 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 to 5.5. 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 Ericales-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 well interval 995–1150 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 favourable 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, which are azonal plant communities, may explain other stratigraphic range extensions that might otherwise be attributed to recycling. “A zonal plant community corresponds more or less to a climatic climax community and an azonal community to an edaphic climax community controlled primarily by extreme soil conditions.... The aquatic vegetation in particular shows very little dependence on zonal climates” (Mueller-Dombois and Ellenberg, 1974, p. 408). Azonal communities occur in similar conditions in several vegetation zones because they are less subject to the climatic stresses that are critical to the formation of the zones, especially water availability or temperature extremes. From a biostratigraphic perspective, azonal environments may allow taxa to persist upsection in spite of changing climatic conditions. This could be an important consideration in palynostratigraphy and the occurrence of relict taxa. The modern redwood species, *Taxodium*, in wetlands of southeastern United States may be an example of such a relict survival. Similarly, A.R. Sweet (pers. comm., 29 March 2010) has noted that relict ‘Maastrichtian’ taxa preferentially occur in the earliest Paleocene in coaly shale and coal, suggesting that the swamp and swamp-margin environment contributed to their survival. In the Mallik case, a near-marine context would have moderated temperature and humidity extremes.

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 900–340 m interval are correct, it would imply continued subsidence on that fault block during that time. If the unconformity below the Iperk Sequence 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 well 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, Pliocene-Pleistocene erosion is likely dominantly controlled by glacial episodes.

SUMMARY

This study of Mallik 5L-38 well 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 paleoenvironmental results for coal samples from core in the 933–1082 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 445–900 m. The +180 μm fraction holds palynomorphs 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 Basin 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 the Mallik 5L-38 well in the 0–270 m interval. *Artemisia* and the apparent sparsity of vegetation are consistent with a late Pliocene-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 340–270 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 deposit 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 regional erosional unconformity below the Iperk Sequence.

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 Early Miocene. 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 acetolyze kerogen samples below 550 m probably indicates some lithological change. There may be an event or disconformity or 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 Oligocene. Strata from 900 m to 850 m probably represent the Early Oligocene, and experimental climate proxy ratios generated in the Mallik 2L-38 well study and in this study suggest that it is a cool interval with temperatures rising stratigraphically upward in this interval, but the following caveats must be heeded. The 850–700 m interval is thought to be Late Oligocene, 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 Mallik 2L-38 and Mallik 5L-38 wells means that there is more to be learned about this technique and the geological context in which it is applied. Low pollen counts and statistical noise are factors, but one 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 and paleoenvironmental regime associated with global cooling in the earliest Oligocene.

Coal samples from core, 933.65–1081.90 m

Fourteen samples from coal bed cores in the 933.65–1081.90 m interval yielded palynological evidence and greatly reduces 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 coal samples allow a confident interpretation of age, paleoclimate, paleoenvironment and may help explain stratigraphic range extensions.

The palynology, sedimentology, and geochemical and organic matter analysis of Mallik 5L-38 and adjacent Mallik 2L-38 wells 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 the Mallik 2L-38 well are compatible with this environmental setting and with a Late Eocene age.

Floral modernization in the Eocene significantly deprives palynologists 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 coal beds 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 coal samples 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 the geographic or environmental ranges of which diminished to the point where they 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 that could be addressed by future work.

1. Is it a valid assumption that is applied here and in the study of Mallik 2L-38 well; i.e. that recycling is relatively chaotic, and that nonchaotic 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 $+180\ \mu\text{m}$ fraction? Is it restricted to the strata penetrated in the 445–900 m interval of the Mallik wells or is it stratigraphically more extensive? Wherever recycling by the same vector 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 analyzing 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 analytical standpoint, recycling presents a continuous challenge, but the recycling patterns are evidence of regional 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 13–20 g were available for this study, but should have been larger. The proportion of fine- and coarse-grained rocks in the strata penetrated and the availability of larger core or cutting samples limits this objective.
4. Why is the palynostratigraphic representation of the Oligocene taxonomically inconsistent among 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 undersaturated 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 Mallik 2L-38 well study is whether palynomorphs leaked from $+180\ \mu\text{m}$ fraction into the kerogen preparation in the Mallik 2L-38 well study. A comparison of the processing techniques and 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 m and 670 m, and some leakage of recycled taxa into the kerogen is one possible contribution to the difference.
6. Organic petrography and fluorescence microscopy may shed light on the composition and origin of the $+180\ \mu\text{m}$ fraction. Knowledge is required of the stratigraphic interval for which the $+180\ \mu\text{m}$ fraction should be separated.

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 among coarser beds, the average pollen productivity in a cuttings sample would be low.
8. Are there identifiable associations among 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 palynostigraphy in the Beaufort-Mackenzie Basin, and in so doing will improve understanding of both this frontier hydrocarbon basin and of high-latitude environmental change in the mid- and late Cenozoic.

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Appendix A

List of taxa names used in this study

The names below derive from modern botanical and paleobotanical names. Authorships of fossil names are cited, but modern names, derived by comparison of specimens with modern pollen atlases and herbarium-based reference collections, are not. The form of the name may be influenced by the constraints of data storage in the biostratigraphic program, Stratabugs, used to load and store these data. For example, a family name, such as Caryophyllaceae, may be a reasonable limit of identification in the palynology of modern flora, and can stand on its own in botanical usage; however, the dictionary for Stratabugs requires a binomial nomenclature, so in that database, the family has been put in the genus field, and 'undiff.' in the species field.

Unknown pollen and spores that have distinctive morphology and that may be of future biostratigraphic value are designated by 'Mallik5L-38' in the genus field, and 'unknown nn' in the species field. This usage is informal nomenclature, but securely designates the palynomorph so that it can be named when appropriate and modified in the database, without affecting taxa not found in the well. This is preferable to using a designation such as 'Species A'.

On palynological slides, acid-resistant specimens are often encountered that have unclear morphology and the taxonomic affinity of which is uncertain. Nonetheless, these specimens may be noted and the slide co-ordinates recorded in case that they recur in subsequent samples. These are designated as 'Unknown sp. A', 'B', and 'C', and the letter indicates only the sequence of finding them on a slide. 'Unknown sp. A' is not the same entity as a specimen of the same name in other slides or wells. It is merely a placeholder for an unusual object the co-ordinates and partial description of which were noted. 'Unknown spp.' holds the count of palynomorphs that were not identified and were not noteworthy.

ACRITARCHS

Micrhystridium sp.

Verhachium sp.

ALGAE

Ovoidites ligneolus (Potonié) Potonié 1966

Sigmopollis sp.

Sigmopollis carbonis (Newman) Srivastava 1984

Botryococcus sp.

Algae spp.

ANNELIDS

Scolecodont undiff.

DINOFLAGELLATES CYSTS

Chatangiella ditissima (McIntyre) Lentin and Williams 1976

Chatangiella verrucosa (Manum) Lentin and Williams 1976

Circulodinium distinctum (Deflandre and Cookson) Jansonius 1986

Dinoflagellate indet.

Filisphaera filifera Bujak 1984

Habibacysta tectata Head, Norris and Mudie 1989

Labyrinthodinium truncatum Piasecki 1980

Odontochitina operculata (Wetzel) Deflandre and Cookson 1955

Palaeocystodinium golzowense Alberti 1961

Peridinioid dinoflagellate

Polysphaeridium zoharyi (Rossignol) Bujak, Downie, Eaton and Williams 1980

Polysphaeridium sp.

Spiniferites sp.

FORAMINIFERA

Microforaminiferal test lining

FUNGI

Brachysporisporites sp.

Brefeldiellites sp.

Desmidiospora willoughbyi (Bradley) Ethridge Glass, Brown and Elsik 1986

Dicellaesporites sp.

Didymoporisporonites sp.

Didymoporisporonites conicus Kalgutkar 1997

Diporisporites sp.

Diporisorites major Chandra, Saxena and Setty 1984
Foveodiporites sp.
Fractisporonites sp.
Fungal hyphae
Fungal hyphae type D of Norris (1986)
Fungal hyphae type A of Norris (1986)
Fungal hyphae type B of Norris (1986)
Helicosporiates pirozynskii Kalgutkar and Siegler 1995
Hypoxylonites sp.
Inapertisporites sp.
Involutisporonites sp.
Lacrimasporonites sp.
Microsporonites sp.
Monoporisporites sp.
Multicellaesporites sp.
Multicellites sp.
Papulosporonites sp.
Phragmothyrtes spp.
Pluricellaesporites sp.
Polyadosporites sp.
Reduviasporonites sp.
Scolecospirites scalaris (Kalgutkar) Kalgutkar and Jansonius 2000
Staphlosporonites sp.
Staphlosporonites elsikii Ramanujam and Srisailam 1980
Striadiporites inflexus (Ke and Shi) Norris 1986
Striadiporites multistriatus (Ke and Shi) Norris 1986
Trichopeltina sp.
Trichothyrites sp.
Unknown fungal spp.

BRYOPHYTES, FERNS, AND FERN ALLIES

Appendicisporites sp.
Baculatisporites crassiprimarius (Kruttsch) Norris 1986
Baculatisporites quintus (Thompson and Pflug) Kruttsch sensu Norris 1986
Baculatisporites sp.

Cicatricosisporites dorogensis Potonié and Gelletich 1933
Cicatricosisporites australiensis (Cookson) Potonié 1956
Cicatricosisporites paradorogensis Kruttsch 1959
Cicatricosisporites hallei Delcourt and Sprumont 1955
Cicatricosisporites subrotundus Brenner 1963
Cicatricosisporites sp.
Cicatricosisporites spiralis Singh 1971
Deltoidospora sp.
Distaltriangulisporites perplexus (Singh) Singh 1971
Distaltriangulisporites irregularis Singh 1971
Equisetum sp.
Gleicheniidites senonicus Ross 1949
Gleicheniidites circinidites (Cookson) Dettmann 1963
Hamulatisporis sp.
Klukisporites foveolatus Pocock 1964
Kuylisporites lunaris Brenner 1962
Laevigatosporites sp.
Lycopodium annotinum/complanatum
Lycopodium spike
Lycopodium sp.
Mallik2L-38 unknown 14*
Mallik5L-38 unknown 02*
Osmunda sp.
Polypodiaceae-Dennstaedtiaceae form 1 of Martin and Rouse (1966)
Polypodiaceae-Dennstaedtiaceae form 2 of Martin and Rouse (1966)
Reticuloidosporites pseudomurii Elsik 1968
Reticulosporis oligocaenicus Kruttsch 1967
Reticulosporis sp.
Selaginella selaginoides
Selaginella sp.
Selaginella microdendron-type
Sphagnum sp.
Stereisporites antiquasporites (Wilson and Webster) Dettmann 1963
Stereisporites microgranulus sensu Norris 1986

Stereisporites maximalis Krutzsch 1963
Tigrisporites sp.
Verrucosiporites obscurilaesuratus Pocock 1962

GYMNOSPERMS

Abies sp.
Araucariacites australis Cookson 1947
Classopollis classoides Pflug emend. Pocock and Jansonius 1961
Inaperturopollenites dubius (Potonié) Thomson and Pflug 1953
Larix/Pseudotsuga-type of White and Ager (1994)
Magnoliaceae undiff.
Picea sp.
Pinaceae undiff.
Pinus sp.
Pinus koraiensis-type of White and Ager (1994)
Podocarpus sp.
Pristinuspollenites sp.
Sciadopitys sp.
Taxodiaceae-Cupressaceae-Taxaceae of White and Ager (1994)
Tsuga sp.
Tsuga canadensis-type of White and Ager (1994)
Tsuga heterophylla-type of White and Ager (1994)
Vitreisporites pallidus (Reissinger) Nilsson 1958

ANGIOSPERMS

Acer sp.
Aesculipollis wyomingensis Pocknall and Nichols 1996
Ailanthipites fluens Norris 1997
Alnus 3-porate
Alnus 4-porate
Alnus 5-porate
Alnus 6-porate
Alnus 7-porate
Alnus sieboldiana-type
Apiaceae
Aquilapollenites sp.

Arecipites symmetricus Krutzsch 1970
Arecipites sp.
Artemisia sp.
Asteraceae
Azonia sp.
Azonia pulchella Felix and Burbidge 1973
Azonia cribrata Wiggins 1976
Betula ≤20 µm
Betula >20 µm
Boisduvalia clavatites Piel 1971
Callistopollenites sp.
Caprifoliaceae
Carya sp.
Caryophyllaceae
Castanea-type of White and Ager (1994)
Celtis-type
Celtispollenites tschudyi (Elsik) Norris 1997
Cercidiphyllum sp.
Chenopodiaceae
Cornus sp.
Corylus-type
Cranwellia sp.
Diervilla/Weigela sp.
Ericales
Fagus sp.
cf. *Fagus* sp.
Fraxinus sp.
Hazaria sheopariariae Srivastava 1971
Ilex-type of White and Ager (1994)
Iridaceae-Liliaceae
Juglans sp.
Jussiaea (Ludwigia) sp.
Kurtzipites sp.
Labrapollis sp.
Liliaceae
Liliacidites mirus Srivastava 1969
Liquidambar sp.
Lonicerapollis gallwitzii Krutzsch 1962

Magnolia sp.
 Mallik5L-38 unknown 01*
 Mallik5L-38 unknown 04*
 Mallik5L-38 unknown 05*
 Mallik5L-38 unknown 06*
Mancicorpus sp. of Ridgway et al. (1995)
Momipites wyomingensis Nichols and Ott 1978
Nymphaea sp.
Nyssa sp.
 Onagraceae
Pachysandra-Sarcococca spp.
Paraalnipollenites alterniporus (Simpson) Srivastava
 1975
Pistillipollenites macgregorii Rouse 1962
 Poaceae
Proteacidites sp.
Psilastephanocolpites cf. *marginatus* Gonzales Guzman
 of Norris (1997)
Psilastephanocolpites sp.
Pterocarya sp.
Quercus sp.
Retimonocolpites sp.
Retitricolpites sp.
Retitricolporopollenites sp.
Rhus-type
 Rosaceae
Rousea sp.
Shepherdia canadensis-type
Singularia sp.
Sparganium sp.

Striatocorpus sweetii White 2009
Striatocorpus sp.
 Tetrad pollen (scabrate)
 Tetraporate
Tilia-type of White and Ager (1994)
Triatriopollenites granilabratus (Stanley) Norton in
 Norton and Hall (1969)
Triatriopollenites pulcher (Simpson) Parsons 2000
 Tricolpate type H of Parsons (2000)
Tricolpites sp.
Tricolpopollenites sp.
Tricolporopollenites sp.
 Triporate type D of Parsons (2000)
Tripoporollenites sp.
Trudopollis sp.
 Tubuliflorae
Ulmus-type of White and Ager (1994)
Viburnum? sp. cf. *V. cassinoides* of McIntyre (1991)
Wodehouseia spinata Stanley, 1961
Wodehouseia sp.
Zelkova-type of Leopold and Liu (1994)

RECYCLED AND UNDETERMINABLE

Recycled palynomorphs
 Undeterminable spp.
 Unknown sp. A, B, or C*
 Unknown spp. *
 * See explanation above.

Appendix B

Palynological analysis records for Mallik 5L-38 well

A list of raw results of the palynological analysis of the Mallik 5L-38 well is found in the file [bu_604_gsc_Appendix_B.pdf](#). This Appendix has not been edited to Geological Survey of Canada specifications. The data are listed per sample by sample depth. The listing per sample details the taxa identified, and the count or relative abundance of each taxon, and comments.

The comments field below a taxon may give a specimen size in polar or equatorial or maximum dimension format, a digital image number (nnnn.jpg or nnnn.tif) in the author's

digital photographic records, the microscope slide letter, and stage co-ordinates (in millimetres) for the specimen. The stage co-ordinates are for a Zeiss Axiophot photomicroscope at GSC Calgary, stage number 45 35 02 [02], with traverse controls set to the right. These co-ordinates may be converted to absolute co-ordinates from the upper right corner of the slide (with the label to the left and facing the observer) by subtracting 61.9 mm from the 'X' co-ordinate and 0.6 m from the 'Y' co-ordinate.

Plate captions

The format of the captions for Plates 1–5 is as follows:

Plate number. Figure number. Taxon name, Dimension measured: measurement, Geological Survey of Canada Type number. Taxonomic comments. Curation (C-) number, Depth, Palynology Lab Preparation (P) number, England Finder Co-ordinate.

Photographs were taken with differential interference contrast microscopy unless otherwise indicated.

Plate 1

Figure 1. *Brefeldiellites?* sp., longest visible dimensions: 122 μm and 96 μm , GSC 135897. This specimen has the cuboidal to rectangular cells of *B. fructiflabella* Dilcher 1965. They are irregularly arranged, similar to the illustration in Dilcher (1965, p. 13, Fig. 104, 106), but not radially prosenchymatous and without a fimbriate margin as he describes. This specimen is multi-ostiolate like the illustration in Kalgutkar and Jansonius (2000, Pl. 24, fig. 9). C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: H53/3.

Figure 2. *Desmidiospora willoughbyi* (Bradley) Ethridge Glass, Brown and Elsik 1986, single longest visible dimension: 28 μm , GSC 135898. See Ethridge Glass, et al. (1986, Pl. 2, fig. 1). C-400979, depth 1005.17–1005.18 m, P4672-162a, England Finder Co-ordinate: P65.

Figure 3a. (amb), 3b (striae near 3 o'clock and 5 o'clock). Mallik5L-38 unknown 01, single longest visible dimension: 28 μm , GSC 135899. Apertures obscure, apparent double-walled exine and faint striate ornament visible near amb on part of the specimen. C-432729, depth 660–660 m, P4672-111c, England Finder Co-ordinate: Q40.

Figure 4. Fungal hypha type D of Norris (1986), longest visible dimensions: 110 μm and 6 μm , GSC 135900. See Norris (1986, Pl. 4, fig. 11–14). C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: J63.

Figure 5. *Baculatisporites quintus* (Thompson and Pflug) Krutzsch *sensu* Norris, 1986, single longest visible dimension: 58 μm , GSC 135901. See Norris (1986, Pl. 7, fig. 23, 24). This and *Baculatisporites crassipramarius* are difficult to separate, but *B. quintus* is used here for spores with ornament that is more pronounced and denticulate. C-432739, depth 710–710 m, P4672-121c, England Finder Co-ordinate: K61.

Figure 6. *Papulosporonites* sp., longest visible dimensions: 64 μm and 24 μm , GSC 135902. See Kalgutkar and Jansonius (2000, Pl. 18, fig. 5–12). C-400979, depth 1005.17–1005.18 m, P4672-162a, England Finder Co-ordinate: P63.

Figure 7. *Papulosporonites* sp., longest visible dimensions: 44 μm and 26 μm , GSC 135903. See Kalgutkar and Jansonius (2000, Pl. 18, fig. 5–12). C-432645, depth 240–240 m, P4672-27a, England Finder Co-ordinate: U63.

Figure 8. *Larix-Pseudotsuga* sp., longest visible dimension: 60 μm and 52 μm , GSC 135904. See White and Ager (1994, p. 70). C-432681, depth 420–420 m, P4672-63a, England Finder Co-ordinate: W61.

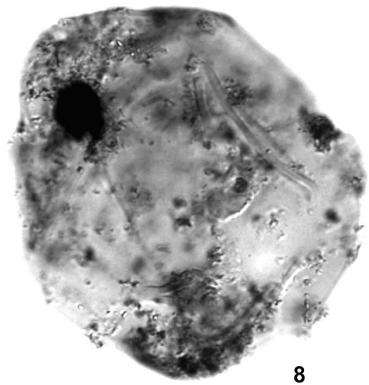
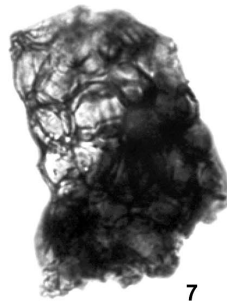
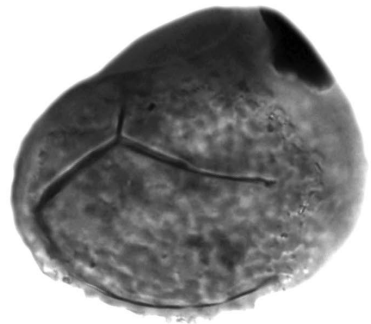
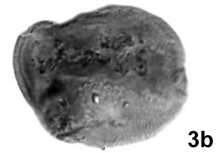
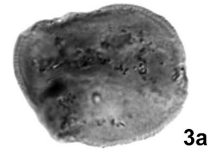
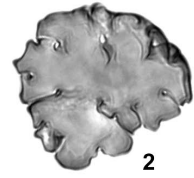
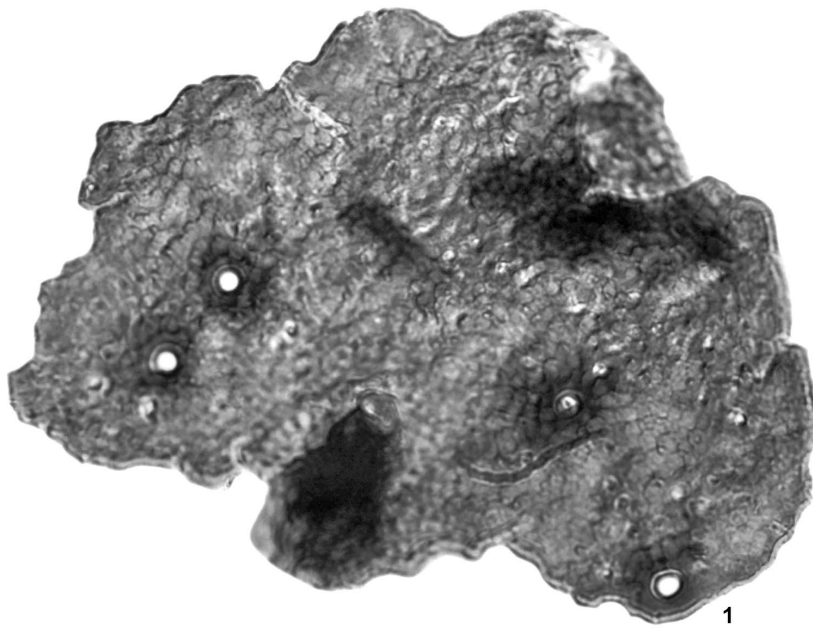


Plate 2

Figure 1a. (proximal), 1b (distal). *Baculatisporites crassiprimarius* (Krutzsch) Norris 1986, longest visible dimensions: 58 μm , GSC 135905. See *B. crassiprimarius* in Norris (1986, Pl. 7, fig. 16, 19–21). C-432719, depth 610–610 m, P4672-101c, England Finder Co-ordinate: J44/4.

Figure 2. *Magnolia* sp., longest visible dimensions: 44 μm and 28 μm , GSC 135906. See Lieux (1980a, Pl. IX–XIII). C-432579, depth 1081.87–1081.9 m, P4672-171a, England Finder Co-ordinate: H49/1.

Figure 3. *Nyssa* sp., equatorial axis: 32 μm , GSC 135907. Compare with Lieux (1983, Pl. XCV and XCVI). C-400981, depth 1005.35–1005.38 m, P4672-164a, England Finder Co-ordinate: H63.

Figure 4. *Picea* sp., longest visible dimensions: 106 μm and 64 μm , GSC 135908. See Kapp et al. (2000, p. 41–45). C-432548, depth 1053.67–1053.68 m, P4672-170b, England Finder Co-ordinate: P56/3.

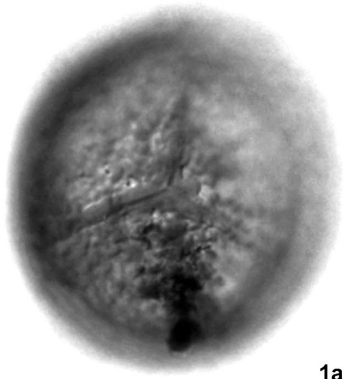
Figure 5. *Pinus* sp., longest visible dimensions: 112 μm and 108 μm , GSC 135909. See Kapp et al. (2000, p. 41–45). C-432548, depth 1053.67–1053.68 m, P4672-170b, England Finder Co-ordinate: D58/3.

Figure 6. *Tsuga canadensis*-type, equatorial axis: 76 μm , GSC 135910. See discussion in White and Ager (1994, p. 70). C-432717, depth 600–600 m, P4672-99c, England Finder Co-ordinate: N55/1.

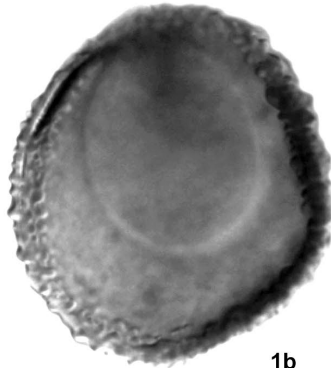
Figure 7a. (phase contrast), 7b (differential interference contrast). *Aesculus wyomingensis* Pocknall and Nichols 1996, (also known as Mallik5L-38 unknown 03,) polar and equatorial axes: 24 μm and 19 μm , GSC 135911. This specimen is similar to Parsons' (2000, Pl. 4, fig. 24, 31–39) *Aesculipollis wyomingensis* Pocknall and Nichols 1996/*Acanthacidites* (?) sp. Norris 1997. The expression of the pore seems variable, but might be a useful taxonomic feature. This species is also similar to *Aesculus* (Heath, 1984) in the striate, microreticulate exine and open, ladder-like baculae on colpus margins, except that *Aesculus* has a distinct pore, whereas this specimen has an erose area. C-432731, depth 673.33 m, P4672-113b, England Finder Co-ordinate: X57/1.

Figure 8. *Lonicera pollis gallwitzii* Krutzsch 1962, polar and equatorial axes: 40 μm and 36 μm , GSC 135912. See Norris (1997, Pl. 6, fig. 30–32) and note the thin echinae and thick, collumellate tectum. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: Q57/3.

Figure 9a, 9b. *Artemisia* sp., equatorial axis: 14 μm , GSC 135913. See McAndrews et al. (1973, Fig. 15E). C-432649, depth 260–260 m, P4672-31, England Finder Co-ordinate: U53/3.



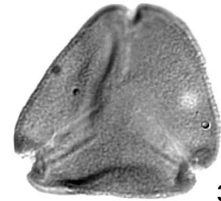
1a



1b



2



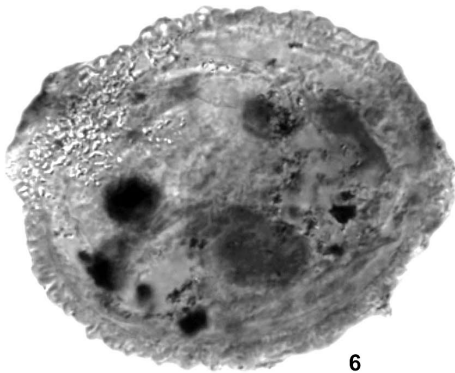
3



4



5



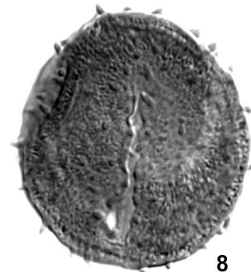
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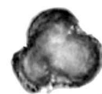
7a



7b



8



9a



9b

Plate 3

Figure 1. *Lonicerapollis gallwitzii* Krutzsch 1962, equatorial axis: 40 μm , GSC 135914. See Norris (1997, Pl. 6, fig. 30–32). Polar view. See Norris (1997, Pl. 6, fig. 30–32) and note the thin echinae and thick, collumellate tectum. C-400953, depth 940.94–940.95 m, P4672-161a, England Finder Co-ordinate: F63/2.

Figure 2a. (spines), 2b (tectum on amb). *Lonicerapollis gallwitzii* Krutzsch 1962, equatorial axis: 46 μm , GSC 135915. See Norris, (1997, Pl. 6, fig. 30–32). C-432530, depth 1043.31–1043.32 m, P4672-168b, England Finder Co-ordinate: L62.

Figure 3. Mallik5L-38 unknown 06, polar and equatorial axes: 38 μm and 28 μm , GSC 135916. This tricoplate grain has a prominent angular reticulum becoming finer toward the colpus margins; 3a) colpus, 3b) intercolpium reticulum. C-432530, depth 1043.31–1043.32 m, P4672-168b, England Finder Co-ordinate: N41/4.

Figure 4. ?*Viburnum* sp. cf. *V. cassinoides* of McIntyre (1991), single longest visible dimension: 30 μm , GSC 135917. This specimen has the distinct membranous reticulum formed with prominent nodes, and a hint of short copli, similar to McIntyre's specimen (1991, Pl. 3, fig. 19–21). In this specimen, the distinct copli are visible, but the faint pore shown in McIntyre's Plate 3, figure 19 is not evident. This polar view shows that it is tricolpate and shows the nodularity on the muri of the reticulum. C-432579, depth 1081.87–1081.90 m, P4672-171a, England Finder Co-ordinate: O57/1.

Figure 5a. (reticulum, note granules on tectus), 5b (high focus showing nodularity of reticulum). cf. ?*Viburnum* sp. cf. *V. cassinoides* of McIntyre (1991), longest visible dimension: 28 μm and 24 μm , GSC 135918. This specimen has the distinct membranous reticulum formed with prominent nodes, and a hint of short copli shown by McIntyre (1991, Pl. 3, fig. 20). A distinct colpus is evident in this specimen, but a faint pore is not. Phase contrast images. C-432579, depth 1081.87–1081.9 m, P4672-171a, England Finder Co-ordinate: K61/4.

Figure 6. Ilex-type, longest visible dimensions: 28 μm and 24 μm , GSC 135919. Ilex-type is discussed in White and Ager (1994, p. 73, Pl. 5, fig. 14). Phase contrast image. C-400979, depth 1005.17–1005.18 m, P4672-162a, England Finder Co-ordinate: E53/1.

Figure 7a, 7b, 7c (phase contrast image of pore area). cf. *Fagus* sp., polar and equatorial axes: 32 μm and 28 μm , GSC 135920. The tricolpate specimen shows only a faint hint of a pore within the undulation of the low verrucae. McAndrews et al. (1973, Fig. 13j, k) and Lieux (1980b, Pl. XXXVIII) show *F. sylvatica* and *F. grandifolia* (respectively) with a faint polar-elongated pore. C-432530, depth 1043.31–1043.32 m, P4672-168b, England Finder Co-ordinate: K64.

Figure 8. *Quercus* sp., polar and equatorial axes: 22 μm and 20 μm , GSC 135921. This grain has a faintly developed pore in the colpus. Compare this specimen with Adams and Morton (1972, Pl. 15, 16) or Lieux (1980b, Pl. XXXIX–XLVI). C-400979, depth 1005.17–1005.18 m, P4672-162a, England Finder Co-ordinate: V46/2.

Figure 9. *Rhus*-type, polar and equatorial axes: 31 μm and 26 μm , GSC 135922. Compare this specimen with Gray (1985, Pl. 12, fig. 1–3). Note the transverse pore and thickenings of furrow margin. C-432530, depth 1043.31–1043.32 m, P4672-168b, England Finder Co-ordinate: M36/4.

Figure 10. *Shepherdia canadensis*-type, polar and equatorial axes: 30 μm and 12 μm , GSC 135923. This grain has a thick exine, strongly demarcated, circular pore and verrucate intercolpium. It is somewhat elongated, which may be due to compression. Compare this specimen with McAndrews et al. (1973, Fig. 13n, o). *Shepherdia canadensis*-type is used because of Matthews and Fyles (2000) indicated the existence of an extinct species of *Shepherdia* in the late Tertiary on Ellesmere Island. C-432620, depth 105–110 m, P4672-2b, England Finder Co-ordinate: F67.

Figure 11. *Cornus* sp., polar and equatorial axes: 28 μm and 14 μm , GSC 135924. This grain has a long, slit-like colpus and a nondistinct pore. The exine is thick, but appears to be largely psilate or somewhat scabrate. The geniculus at the faint pore suggests that this is *Cornus* (see McAndrews et al., 1973, Fig. 13p, q and Fig. 14a–c). It was identified as *Shepherdia canadensis* previously in GSC Open File 6882 (White, 2012). C-432659, depth 310–310 m, P4672-41a, England Finder Co-ordinate: O65/3.

Figure 12. *Psilastephanocolpites* cf. *marginatus* Gonzales Guzman of Norris (1997), polar and equatorial axes: 26 μm and 22 μm , GSC 135925. Re-examination of the Adgo F-28 specimen illustrated by Norris (1997, Pl. 6, fig. 34), stored with the type collection at GSC Calgary, shows that it is a tetracolpate grain, polar and equatorial axes: 23 μm and 22 μm . This Mallik 5L-38 specimen is also tetracolpate and similarly sized, but somewhat more prolate than the specimen from the Adgo F-28 well. The colps are about half the length of the grain in both specimens and both grains are psilate. The copli appear to be offset from the equator on both grains, but this might be due to oblique grain compression. C-432530, depth 1043.31–1043.32 m, P4672-168b, England Finder Co-ordinate: E46/4.

Figure 13. *Carya* sp., equatorial axis: 28 μm , GSC 135926. The pores are just off the amb, similar to McAndrews et al. (1973, Fig. 7a) or Adams and Morton (1972, Pl. 10) or Lieux (1980b, Pl. XXXIII, fig. 3). C-400953, depth 940.94–940.95 m, P4672-161a, England Finder Co-ordinate: E63/1.

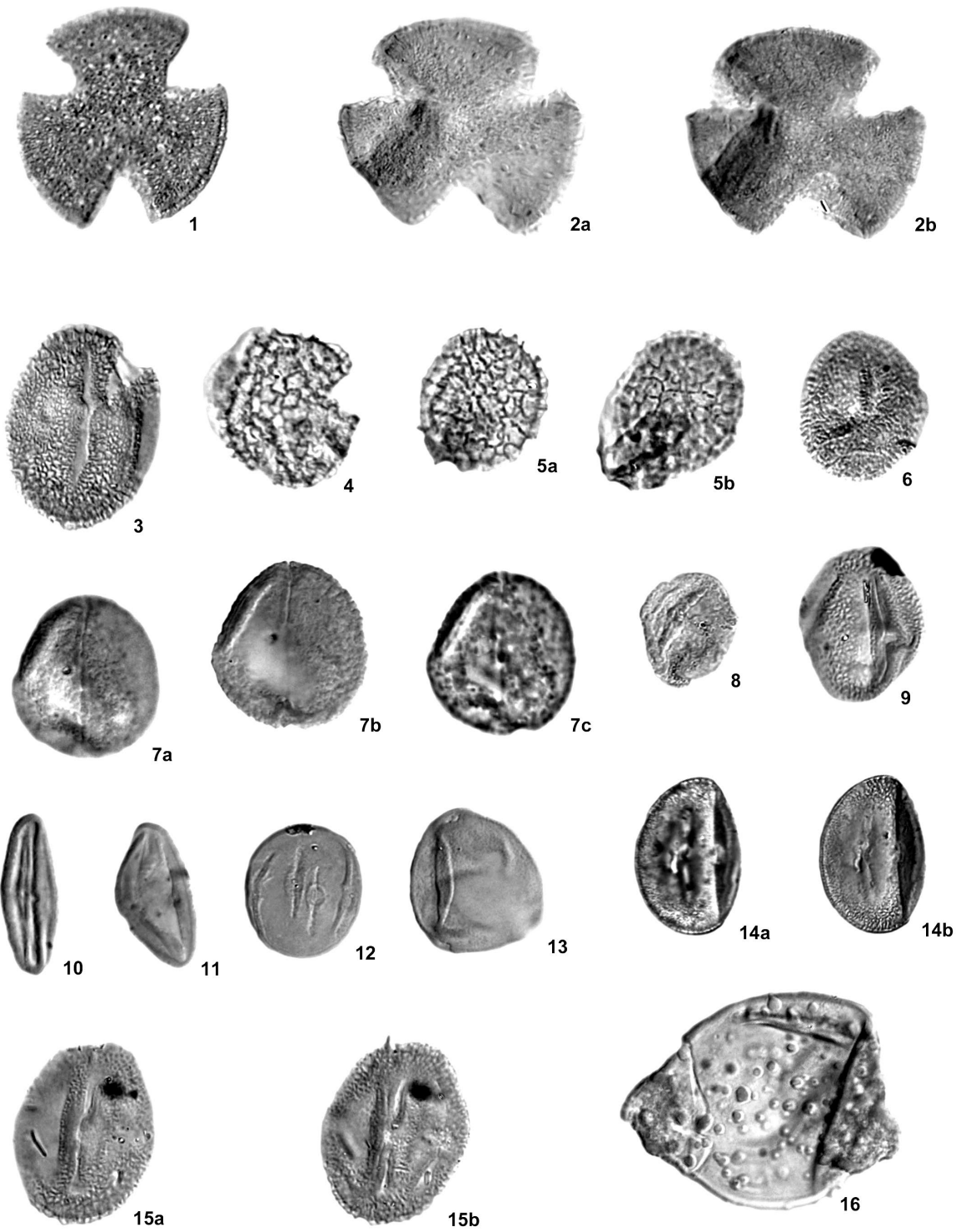


Plate 3 (cont.)

Figure 14a. (phase contrast showing colps), 14b) (differential interference contrast showing rugulate ornament). Mallik5L-38 unknown 05, polar and equatorial axes: 30 μm and 20 μm , GSC 135927. This is a tricolporate grain, rugulate in the intercolpium and the poles, psilate near the colpus. C-432757, depth 800–800 m, P4672-139c, England Finder Co-ordinate: R61.

Figure 15a. (reticulum and pore), 15b (amb). Mallik5L-38 unknown 06, polar and equatorial axes: 36 μm and 28 μm , GSC 135928. A reticulate tricolporate grain with faint pore; reticulum coarser on poles and intercolpium than along the colpus; the reticulum appears baculate in cross-section, the polar reticulum is thicker with elements that are less clearly baculate. C-432530, depth 1043.31–1043.32 m, P4672-168b, England Finder Co-ordinate: F53/4.

Figure 16. cf. *Boisduvalia clavatites*, equatorial axis: 54 μm , GSC 135929. The widely variable coarseness of the clavae in this Mallik specimen resembles those of *Boisduvalia clavatites* of Piel (1971, Fig. 142, 143). *Diervilla* of McIntyre (1991, Pl. 1, fig. 1, 2) has smaller baculae and/or clavae than this specimen and apparently less range of variability, but distinctly in-turned pores. *Diervilla* of McIntyre (1991) and *Boisduvalia clavatites* Piel 1971 are apparently related, perhaps co-specific. Examination of a larger population would be required. The specimen called *Diervilla* of McIntyre (1991) in the Mallik 2L-38 well (945.20–945.22 m) (White, 2009, Pl. 3, fig. 11) should probably be considered to be *Boisduvalia clavatites*. C-400953, depth 940.94–940.95 m, P4672-161a, England Finder Co-ordinate: O35.

Plate 4

Figure 1. *Diervilla* of McIntyre (1991), equatorial axis: 52 μm , GSC 135930. *Diervilla* of McIntyre (1991, Pl. 1, fig. 1, 2) has smaller clavae than this specimen and apparently less range of variability, but the in-turned pores are very similar. *Diervilla* of McIntyre (1991) and *Boisduvalia clavatites* Piel 1971 are apparently related, perhaps co-specific. Examination of a larger population would be required. The specimen called *Diervilla* of McIntyre (1991) in the Mallik 2L-38 well (945.20–945.22 m) (White, 2009, Pl. 3, fig. 11) should probably be considered to be *Boisduvalia clavatites*. C-432530, depth 1043.31–1043.32 m, P4672-168b, England Finder Co-ordinate: H52/3.

Figure 2. *Jussiaea (Ludwigia) sp.*, equatorial axis: 46 μm , GSC 135931. See Piel (1971, Fig. 152, 153). C-400953, depth 940.94–940.95 m, P4672-161a, England Finder Co-ordinate: G39/4.

Figure 3. *Pistillipollenites macgregorii* Rouse 1962, equatorial axis: 40 μm , GSC 135932. The brevicolpus bordered by one gemma is visible beside a colpus on this specimen. This specimen is larger than the size range given by Rouse and Srivastava (1970), but it is probably due to compression. C-432530, depth 1043.31–1043.32 m, P4672-168b, England Finder Co-ordinate: N46/2.

Figure 4a, 4b. ?*Momipites wyomingensis* Nichols and Ott 1978, equatorial axis: 30 μm , GSC 135933. This specimen has slit-like or V-shaped pores that are not distinctly atriate, but the specimen appears to fall in the range of *Momipites wyomingensis* Nichols and Ott 1978, the simplest of the *Momipites* lineage (Nichols and Ott, 1978, Pl. 1, fig. 3, 4). C-432548, depth 1053.67–1053.68 m, P4672-170b, England Finder Co-ordinate: P53/3.

Figure 5. *Alnus sieboldiana*-type, equatorial axis: 28 μm , GSC 135934. Phase contrast shows the central annulus of this eroded specimen. Simpson (1960) noted *Alnus* with a distinct central annulus is similar to modern Japanese species, *A. sieboldiana* and *A. firma* (p. 443, Pl. XIII, fig. 9, 9a). *A. firma* is illustrated by Shimakura (1973, Pl. 11, fig. 82) and has a faint annulus, but it is partly formed by the arci, rather than being as distinct and centrally located as this Mallik specimen and Simpson's (1960) Plate XIII, figure 9a illustration of *A. sieboldiana*. *Alnus scotica* is Simpson's name for this morphotype, but the preference in this document is for a name that shows the close modern botanical affinity. C-432530, depth 1043.31–1043.32 m, P4672-168b, England Finder Co-ordinate: E63.

Figure 6. *Pachysandra-Sarcococca*, longest visible dimension: 42 μm , GSC 135935. Gray and Sohma (1964) distinguished the pollen morphology of modern *Pachysandra* and *Sarcococca* from other Buxaceae. Leopold and MacGinitie (1972) discussed the Cenozoic record. Piel (1971) used *Pachysandra* or *Sarcococca* and McIntyre (1991) used *Pachysandra* for this taxon. *Erdtmanipollis* is the form name for this taxon. C-432530, depth 1043.31–1043.32 m, P4672-168b, England Finder Co-ordinate: K49/2.

Figure 7. Chenopodiineae, longest visible dimension: 19 μm , GSC 135936. The proximal side of this grain is torn, but pores and partial pores are visible on proximal face and on amb. See McAndrews et al. (1973, Fig. 8f). C-432659, depth 310–310 m, P4672-41a, England Finder Co-ordinate: T65.

Figure 8. cf. *Liquidambar sp.*, longest visible dimension: 21 μm , GSC 135937. The image of the exine structure and sculpture shows granulation in pores like *Liquidambar* in Lieux (1980b, Pl. XXV); however, this grain is relatively small and does not appear to have the perforate exine of *Liquidambar*. C-432530, depth 1043.31–1043.32 m, P4672-168b, England Finder Co-ordinate: K37.

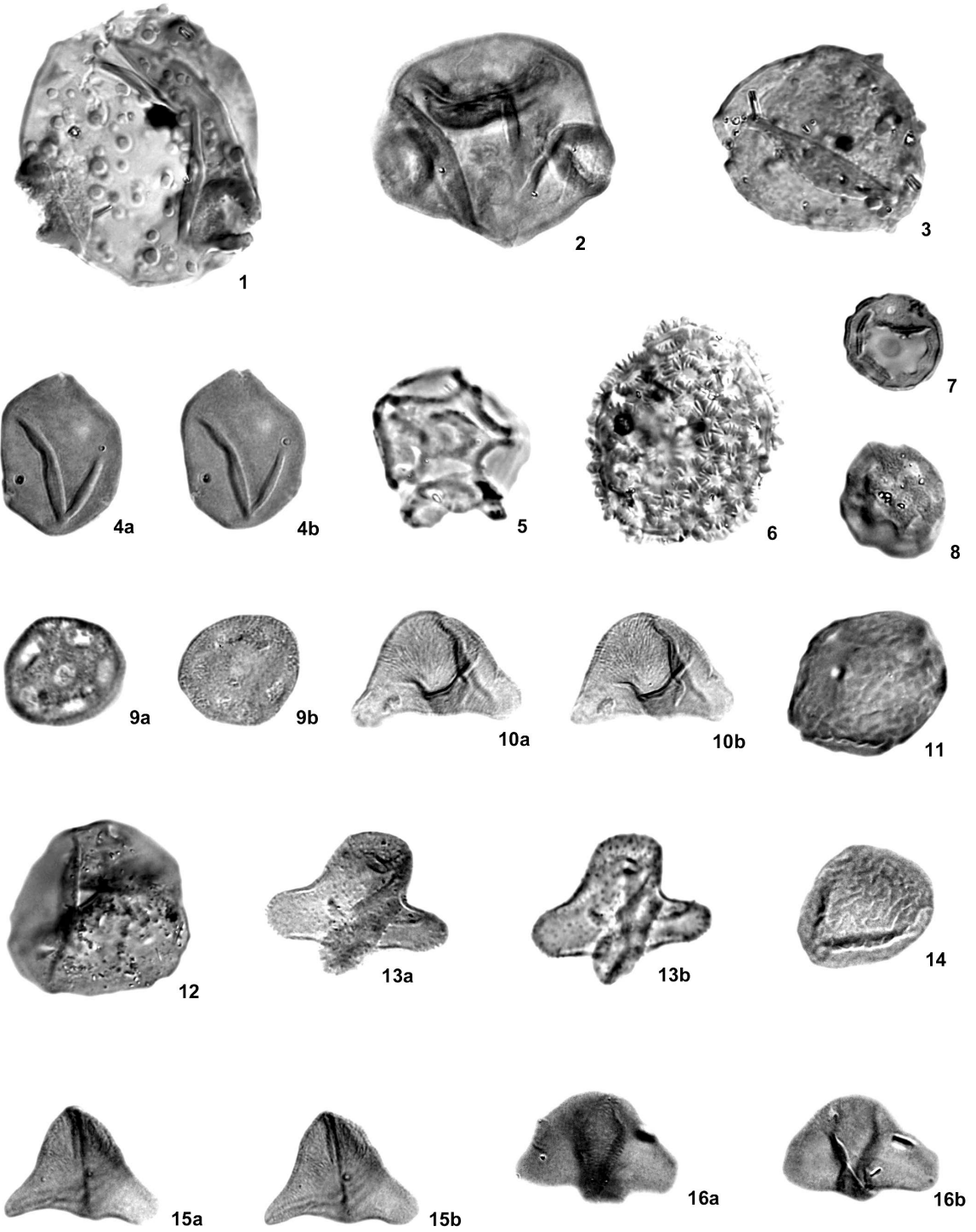


Plate 4 (cont.)

Figure 9a. (phase contrast image shows pores and granulation not apparent in image b), 9b (differential interference contrast image of the exine structure and sculpture showing granulation in pores). *Liquidambar* sp., longest visible dimension: 24 μm , GSC 135938. See Lieux (1980b, Pl. XXV). This grain is smaller than Lieux's illustration, but shows the same pore granulation and perforate exine. C-400979, depth 1005.17–1005.18 m, P4672-162a, England Finder Co-ordinate: N61.

Figure 10a, 10b. cf. *Mancicorpus* sp. of Ridgway et al. (1995), polar and equatorial axes: 32 μm and 20 μm , GSC 135939. This Mallik 5L-38 specimen has narrow projections that descend below a small anatapical dome, similar to *Mancicorpus* sp. of Ridgway et al. (1995, Fig. 13i). Faint striations are visible on Ridgway et al.'s *Mancicorpus* specimen that is stored at GSC Calgary. The stronger striations of this Mallik specimen and the concave amb from pole to apical tip also suggest features of *Striatocorpus sweetii* White 2009 (White, 2009, Pl. 5, fig. 21–23). C-400953, depth 940.94–940.95 m, P4672-161a, England Finder Co-ordinate: L63.

Figure 11. *Ulmus*-type, equatorial axis: 30 μm , GSC 135940. See discussion in White and Ager (1994). C-432924, depth 933.64–933.65 m, P4672-157b, England Finder Co-ordinate: N63/1.

Figure 12. *Pterocarya* sp., equatorial axes: 34 μm , GSC 135941. See Stone and Broome (1975, Fig. 1, f, g) and Shimakura (1973, Pl. 11, fig. 74, 75). C-432729, depth 660–660 m, P4672-111c, England Finder Co-ordinate: G48/4.

Figure 13a. (differential interference contrast), 13b (phase contrast). *Aquilapollenites* sp. cf. *A. quadrilobus*, polar and equatorial axes: 28 μm and 32 μm , GSC 135942. Identified by A.R. Sweet (pers. comm., 23 March 2010). See also Tschudy and Leopold (1970, Pl. 1, fig. 5a). C-432579, depth 1081.87–1081.9 m, P4672-171a, England Finder Co-ordinate: T63.

Figure 14. *Zelkova*-type of Leopold and Liu (1994) equatorial axis: 28 μm , GSC 135943. This specimen is comparable to Leopold and Liu's (1994, Pl. 2, fig. 23) illustration of a three-pored Ulmoideae as *Zelkova*-type. Zavada (1983) indicated that *Z. serrata* has four or five pores so further investigation may require a revision in this usage. C-400953, depth 940.94–940.95 m, P4672-161a, England Finder Co-ordinate: K57/1.

Figure 15a, 15b. cf. *Mancicorpus* sp. of Ridgway et al. (1995), polar and equatorial axes: 20 μm and 30 μm , GSC 135944. This Mallik 5L-38 specimen has narrow projections that descend below a small anatapical dome, similar to *Mancicorpus* sp. of Ridgway et al. (1995, Fig. 13i). Faint striations are visible on Ridgway et al.'s illustrated *Mancicorpus* specimen, confirmed by examination of the specimen stored at GSC Calgary. The differences in width and distal roundness of the projections of this specimen and the different pointedness of the proximal polar dome among this specimen and Plate 4, Figure 10a, b and the Ridgway et al. (1995, Fig. 13i) specimen suggest that there may be considerable variability in shape of this species, or that they may be similar species. More observations of larger populations may yield better taxonomic insights. C-400953, depth 940.94–940.95 m, P4672-161a, England Finder Co-ordinate: L63/4.

Figure 16a. (faint striations on margin of proximal projection), 16b (amb). *Striatocorpus sweetii* White 2009, polar and equatorial axes: 14 μm and 28 μm , GSC 135945. This is a poorly presented specimen, but there does not appear to be an antapical dome and the projections do not descent, so this specimen is *Striatocorpus sweetii* White 2009 (White, 2009, Pl. 5, fig. 21–23): as best one can discern the projections in one image. C-400929, depth 934.2–934.21 m, P4672-159b, England Finder Co-ordinate: F63.

Plate 5

Figures 1–19 illustrate the variation in shapes, sizes, and exine thickness of Ericale tetrahedral tetrads in coal samples between 1005.17 m and 1005.56 m.

Figure 1. Ericale tetrad, single longest visible dimension: 30 μm , GSC 135946. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: O61/1.

Figure 2. Ericale tetrad, single longest visible dimension: 26 μm , GSC 135947. C-400980, depth 1005.3–1005.31 m, P4672-163a, England Finder Co-ordinate: G62.

Figure 3. Ericale tetrad, single longest visible dimension: 26 μm , GSC 135948. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: T59/1.

Figure 4. Ericale tetrad, single longest visible dimension: 26 μm , GSC 135949. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: M59.

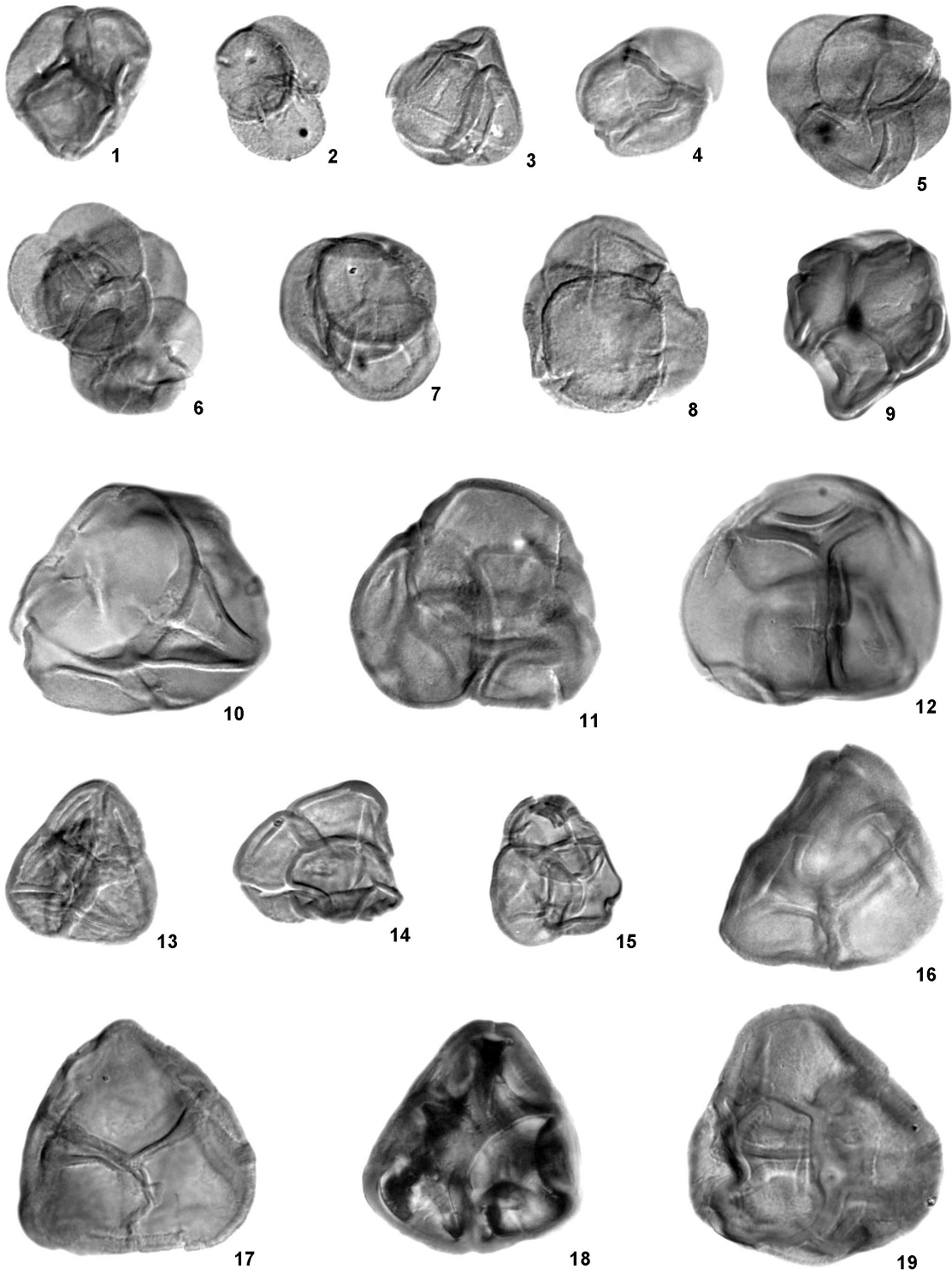


Plate 5 (cont.)

Figure 5. *Ericale* tetrad, single longest visible dimension: 34 μm , GSC 135950. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: U55/3.

Figure 6. *Ericale* tetrads, single longest visible dimension: 27 μm , GSC 135951. Diameter is for tetrad in focus. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: E40.

Figure 7. *Ericale* tetrad, single longest visible dimension: 34 μm , GSC 135952. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: T50/4.

Figure 8. *Ericale* tetrad, single longest visible dimension: 36 μm , GSC 135953. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: E53/1.

Figure 9. *Ericale* tetrad, single longest visible dimension: 36 μm , GSC 135954. C-400981, depth 1005.35–1005.38 m, P4672-164a, England Finder Co-ordinate: L44/1.

Figure 10. *Ericale* tetrad, single longest visible dimension: 48 μm , GSC 135955. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: G46/4.

Figure 11. *Ericale* tetrad, single longest visible dimension: 46 μm , GSC 135956. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: C49/3.

Figure 12. *Ericale* tetrad, single longest visible dimension: 48 μm , GSC 135957. C-400980, depth 1005.3–1005.31 m, P4672-163a, England Finder Co-ordinate: G62.

Figure 13. *Ericale* tetrad, single longest visible dimension: 30 μm , GSC 135958. C-400979, depth 1005.17–1005.18 m, P4672-162a, England Finder Co-ordinate: F62/2.

Figure 14. *Ericale* tetrad, single longest visible dimension: 32 μm , GSC 135959. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: Q59/3.

Figure 15. *Ericale* tetrad, single longest visible dimension: 28 μm , GSC 135960. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: O38.

Figure 16. *Ericale* tetrad, single longest visible dimension: 40 μm , GSC 135961. C-400983, depth 1005.55–1005.56 m, P4672-166a, England Finder Co-ordinate: E53/3.

Figure 17. *Ericale* tetrad, single longest visible dimension: 44 μm , GSC 135962. C-400981, depth 1005.35–1005.38 m, P4672-164a, England Finder Co-ordinate: U37.

Figure 18. *Ericale* tetrad, single longest visible dimension: 43 μm , GSC 135963. C-400979, depth 1005.17–1005.18 m, P4672-162a, England Finder Co-ordinate: H37.

Figure 19. *Ericale* tetrad, single longest visible dimension: 46 μm , GSC 135964. C-400980, depth 1005.3–1005.31 m, P4672-163a, England Finder Co-ordinate: K50/1.