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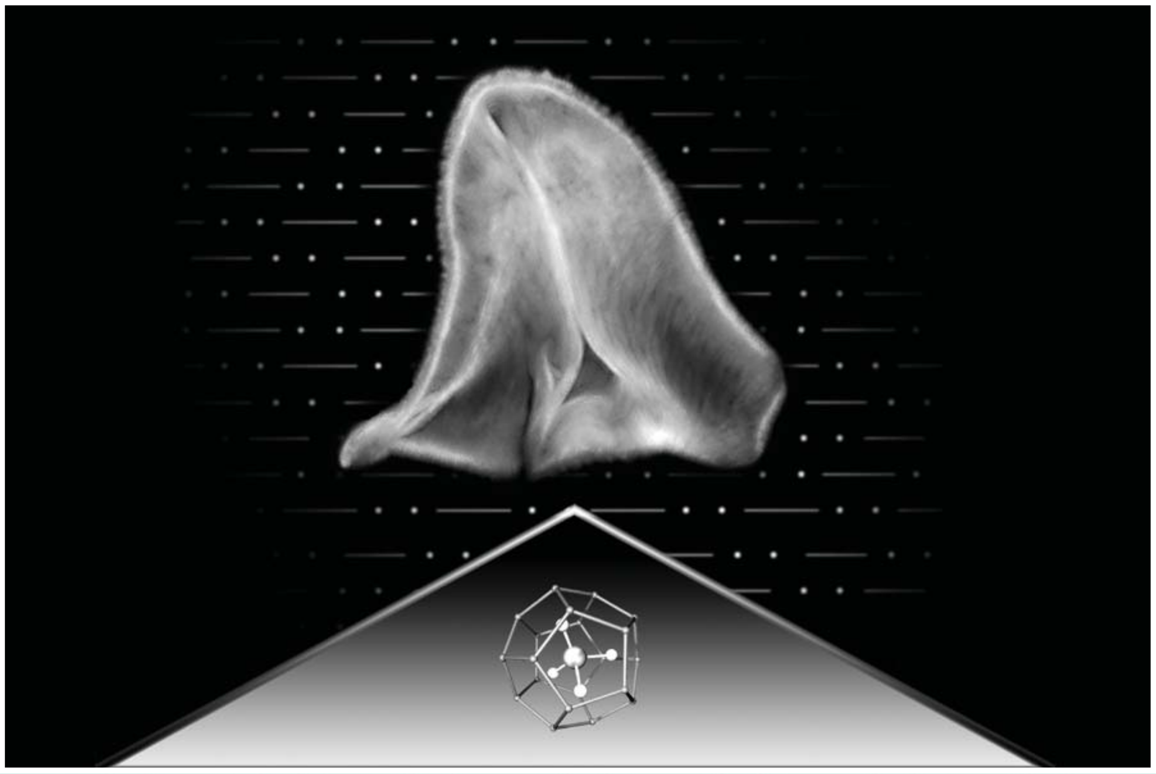

# Palynology, age, correlation, and paleoclimatology from JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well and the significance for gas hydrate: a new approach

**J.M. White**

2009

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

**J.M. White**

**With appendix A by D.H. McNeil**

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**Cover illustration**
The cover photo is a confocal laser scanning image of a paratype of *Striatocorpus sweetii* sp. nov., a new triprojectate pollen grain found between 990 m and 1140 m in Mallik 2L-38. The fossil is shown in a siltstone matrix. The gas hydrate focus of Mallik research is represented by a methane molecule in a solid-water lattice. Cover design by G. Edwards and J. White and *S. sweetii* image by J. Wong.

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# CONTENTS

**Appendices**

**Figures**

**Tables**

**Plates**

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

## *Abstract*

*A quantitative palynological study of a 480 m section of mid-Cenozoic sediment from the Mallik 2L-38 gas hydrate research borehole, Mackenzie River delta, is based on core and high-quality cuttings. The degree of recycling of palynomorphs requires evaluation because recycled palynomorphs can compromise biostratigraphic age determinations. The study proposes that a biologically driven palynomorph series will be more directional and ordered than a series dominated by recycling. The palynological count data are evaluated by several techniques and it is concluded that they present a primary biostratigraphic pattern amenable to interpretation. Results revise previous palynological age determinations. The age of the interval from 1150 m (total depth) to the unconformity at 926 m is interpreted to be Late Eocene, and from the unconformity to 670 m, the top of the cuttings, is Oligocene and perhaps Early Miocene. An experimental approach to refining age determinations is calculation of four independent ratios of pollen taxa that are likely to reflect paleotemperatures, and correlation of the results to the North Atlantic Ocean foraminiferal* $\delta^{18}O$ *curve. Two ratios, (thermophilous angiosperms minus* Ulmus*)/total angiosperms and Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae, are most consistent and suggest a long-term cooling trend culminating about 890 m, tentatively correlated with the early Oligocene cold period. This is at the top of the interval that subsequently hosted gas hydrate, and suggests some mechanism such as lithological change contributed to the gas accumulation. A short core from 110–118 m is Late Pliocene–Pleistocene.*

## *Résumé*

*Une étude palynologique quantitative a été menée sur une coupe de roches sédimentaires du Cénozoïque moyen de 480 m recoupée dans le puits de recherche sur les hydrates de gaz naturel Mallik 2L-38, dans le delta du fleuve Mackenzie, au moyen de carottes et de déblais de forage de grande qualité. Le degré de remaniement des palynomorphes doit être déterminé, car les palynomorphes remaniés peuvent nuire à la datation biostratigraphique. L'étude reposait sur l'hypothèse qu'une série de palynomorphes tributaire de facteurs biologiques est plus directionnelle et ordonnée qu'une série où le remaniement joue un rôle prédominant. À l'aide de plusieurs techniques, on a évalué les données de comptes palynologiques et conclu qu'elles témoignent d'une configuration biostratigraphique primaire propice à une interprétation. Les résultats obtenus ont mené à la révision de datations palynologiques antérieures. Selon nos interprétations, l'âge de l'intervalle allant de 1150 m (profondeur totale) jusqu'à une discordance située à 926 m correspond à l'Éocène tardif, tandis que celui de l'intervalle allant de la discordance jusqu'au sommet des déblais, à 670 m, se situe à l'Oligocène et, peut-être, au Miocène précoce. Une approche expérimentale permettant de préciser les datations consiste à calculer quatre rapports de taxons de pollen indépendants qui peuvent vraisemblablement rendre compte des paléotempératures et à corréler les résultats obtenus avec la courbe de* $\delta^{18}O$ *des foraminifères de l'Atlantique Nord. Le rapport (angiospermes thermophiles à l'exception de* Ulmus*)/angiospermes totaux et le rapport Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae sont les plus cohérents et laissent supposer l'existence d'un refroidissement de longue durée dont le point culminant se manifeste à environ 890 m et que l'on a provisoirement corrélé avec la période froide de l'Oligocène précoce. Ce niveau se situe au sommet de l'intervalle qui renfermera ultérieurement des hydrates de gaz naturel, ce qui laisse croire qu'un certain mécanisme, comme un changement lithologique, aurait contribué à l'accumulation de gaz naturel. Une courte carotte extraite entre 110 et 118 m date du Pliocène tardif au Pléistocène.*

# SUMMARY

The 1150 m deep JAPEX/JNOC/GSC Mallik 2L-38 research well was drilled in 1998 to investigate gas hydrate deposits previously identified in the Mallik L-38 well. The Mallik 2L-38 well gives an uncommon opportunity to contribute to the palynostratigraphy and paleoclimatology of the Beaufort-Mackenzie Basin because the well provides core and high-quality cuttings that span a 480 m section of upper Paleogene and Neogene sediment, plus a short core interval of Pliocene-Pleistocene sediment. Quantitative palynological results are reported in this study to maximize information recovery from palynological assemblages. Percentage diagrams are provided for each taxon and 125 taxa are illustrated.

Recycling of palynomorphs from Cretaceous and older Paleogene strata can confuse age determination and this has presented a persistent problem for interpretation of upper Cenozoic palynological studies in the Beaufort-Mackenzie Basin. The detection of recycling is relatively straightforward if the recycled taxa are significantly older than the strata in which they are found, such as Cretaceous palynomorphs in mid-Cenozoic sediments, or if they are of higher thermal maturity. Detection of recycling is more difficult if the taxa are recycled from rocks not greatly older, and if there are no thermal maturity differences. Determination of recycling usually relies on the professional judgement of individual palynologists. This study attempts a more rigorous approach to the problem of recycling, proposing an approach to evaluate recycling by an assessment of chaotic patterns versus coherent and explicable patterns in the palynological record. The assumption is that patterns in the data that are biologically driven will be directional and ordered, whereas records influenced greatly by recycling will be more random. The presence of random versus coherent patterns is evaluated by quantitative techniques, i.e. palynomorph concentration per gram of sediment, plots of relative abundance of taxa, comparisons of taxa abundance patterns, and statistical tests of randomness of occurrence of rare taxa. Although these analyses assess the coherence of the overall palynological record, they do not ‘prove’ that any individual taxon is or is not recycled. It is concluded that the palynomorph record in Mallik 2L-38 well provides a biostratigraphy suitable for the determination of age and depositional environment of the rocks, even though some recycling is known to be present. These analyses provide a more rigorous approach to the study of recycling, but do not provide a perfect answer.

# SOMMAIRE

Le puits de recherche en profondeur JAPEX/JNOC/GSC Mallik 2L-38 a été foré jusqu’à 1150 m en 1998 afin d’étudier des gisements d’hydrates de gaz naturel découverts précédemment dans le puits Mallik L-38. Le puits Mallik 2L-38 offre une occasion extraordinaire de contribuer à l’étude palynostratigraphique et paléoclimatologique du bassin de Beaufort-Mackenzie, grâce aux carottes et déblais de forage de grande qualité qu’on y a extrait dans une coupe de 480 m de roches sédimentaires du Paléogène supérieur, et du Néogène ainsi qu’à une courte carotte de roches sédimentaires Pliocène-Pléistocène. Des résultats palynologiques quantitatifs figurent dans l’étude afin qu’un maximum de renseignements puissent être recueillis au sujet des associations palynologiques. Des diagrammes y figurent également, ceux-ci présentant des pourcentages relatifs à chaque taxon et ce pour 125 taxons.

Le remaniement de palynomorphes issus de strates crétacées et de strates plus anciennes du Paléogène peut rendre les datations inexactes et a souvent posé problème au moment d’interpréter des études palynologiques des roches du Cénozoïque supérieur dans le bassin de Beaufort-Mackenzie. Il est relativement simple de détecter un remaniement lorsque les taxons remaniés sont beaucoup plus anciens que les strates dans lesquels ils reposent, comme dans le cas des palynomorphes crétacés logés dans des roches sédimentaires du Cénozoïque moyen, ou lorsqu’ils rendent compte d’un niveau de maturité thermique supérieur. Il est plus difficile de le faire lorsque les taxons ont été remaniés à partir de roches qui ne sont pas beaucoup plus anciennes et lorsqu’il n’y a aucune différence de maturité thermique. La détermination du remaniement repose généralement sur le jugement professionnel des palynologues. L’étude est fondée sur une approche expérimentale plus rigoureuse quant au problème du remaniement, laquelle fait appel à une évaluation du remaniement consistant à comparer des configurations chaotiques à des configurations cohérentes et explicables au sein de l’ensemble des données palynologiques. L’hypothèse employée veut que les configurations dans les données tributaires de facteurs biologiques sont plus directionnelles et ordonnées, alors que celles considérablement influencées par le remaniement sont plus aléatoires. L’existence de configurations aléatoires par rapport à celle de configurations cohérentes est évaluée au moyen de techniques quantitatives, à savoir l’établissement des concentrations de palynomorphes par gramme de sédiments, le tracé de l’abondance relative des taxons, la comparaison des distributions d’abondance des taxons et l’analyse statistique du caractère aléatoire des occurrences de taxons rares. Bien que ces techniques permettent d’évaluer la cohérence de l’ensemble des données palynologiques, elles ne fournissent aucune « preuve » qu’un taxon donné a été remanié ou non. On a conclu que l’ensemble des données palynologiques du puits Mallik 2L-38 témoigne d’une biostratigraphie propice à la détermination de l’âge et du milieu de dépôt des roches, même si un certain remaniement a été relevé. Les techniques susmentionnées permettent une étude plus rigoureuse du remaniement, sans toutefois donner une réponse parfaite.

This study presents a correction of a previous palynological age for Mallik 2L-38 strata, and assigns the interval between 1150 m and a disconformity at 926.5 m to the Late Eocene, and the interval between that disconformity and the top of the cuttings at 670 m to the Oligocene and possibly earliest Miocene. This means that some 1000 m more sediment accumulated during the Eocene in Mallik 2L-38 well than evinced by micropaleontology in adjacent Mallik L-38 well. This is because the foraminiferal top of the *Haplophragmoides richardsensis* Zone in Mallik L-38 strata occurs in a shallow-marine environment that changes upward to a continental facies with minor marine incursions. This continental environment was unsuitable for foraminifera, which are largely recycled, but it was suitable for vegetation that produced pollen and spores. This interpretation fits local seismic and regional geological evidence of Late Eocene displacement on the Taglu fault zone, with rapid sedimentation taking place during fault growth. A Late Eocene age for sediment that is lithologically typical of the Kugmallit Sequence is consistent with previous interpretations that part of the eponymous Kugmallit Formation is Late Eocene. The record of recycled palynomorphs suggests acceleration in regional erosion beginning near 1000 m in the well, i.e. in the Late Eocene.

A short interval of core from 110 m to 118 m is Late Pliocene–Pleistocene. It yielded an abundance of recycled taxa consistent with regional erosion, probably by glaciation.

Palynological correlation to the Caribou Hills section is problematic, but the Mallik 2L-38 well disconformity at 926.5 m may be equivalent to Caribou Hills Embryophyte Zone 4b-4c unconformity, or perhaps to some interval within subzone CHE4c. In correlation to the Adgo F-28 well, the Mallik 2L-38 well disconformity at 926.5 m may correlate to the top of the *Integricorpus* Zone; however, *Integricorpus* does not have an abundant and consistent record of occurrence within its range. Consequently, recognition of its last occurrence datum in any individual study can be problematic and the derived correlation is uncertain.

Paleoclimatic changes are a dominant feature of the Cenozoic history. An experimental, paleoclimatic approach is adopted to refine age determinations by correlation of the Mallik palynological series to the North Atlantic Ocean foraminiferal $\delta^{18}O$ curve, which serves as a reference paleotemperature proxy series. Pollen taxa, the modern relatives of which show that they are temperature sensitive, are used to construct experimental curves of relative temperature by calculating ratios of taxa. The ratios are statistically independent, but as experimental constructs, their sensitivity to paleotemperature needs further investigation. These

Dans la présente étude, on corrige une datation palynologique antérieure de strates recoupées dans le puits Mallik 2L-38. On y rattache l'intervalle situé entre 1150 m et une disconformité, à 926,5 m, à l'Éocène tardif et celui situé entre cette disconformité et le sommet des déblais, à 670 m, à l'Oligocène et, peut-être, au Miocène initial. Cela signifie que, contrairement à ce que l'on pouvait déduire de l'étude micropaléontologique du puits Mallik L-38 adjacent, environ 1000 m de sédiments de plus se sont accumulés à l'Éocène au site du puits Mallik 2L-38. Cela s'explique par le fait que les foraminifères au sommet de la Zone à *Haplophragmoides richardsensis*, dans le puits Mallik L-38, reposent dans des roches sédimentaires de milieu marin peu profond qui se changent vers le haut en faciès continental ponctué d'intervalles témoignant de rares intrusions marines. Le milieu continental n'était pas propice aux foraminifères, qui ont été remaniés en grande partie, mais il l'était à la végétation qui produit du pollen et des spores. Cette interprétation correspond aux indices sismiques locaux et aux indices géologiques régionaux qui témoignent d'un déplacement le long de la zone de failles de Taglu pendant l'Éocène tardif, ainsi que d'une sédimentation rapide lorsque les failles étaient actives. Le rattachement à l'Éocène tardif des roches sédimentaires caractéristiques sur le plan lithologique de la Séquence de Kugmallit est compatible avec des interprétations précédentes selon lesquelles cette partie de la Formation de Kugmallit date aussi de l'Éocène tardif. L'ensemble des données sur les palynomorphes remaniés laisse supposer une accélération de l'érosion régionale à environ 1000 m dans le puits, soit à l'Éocène tardif.

Une courte carotte prélevée entre 110 et 118 m date du Pliocène tardif au Pléistocène et présente de nombreux taxons remaniés témoignant d'une érosion régionale probablement attribuable à une glaciation.

La corrélation palynologique avec la coupe des collines Caribou pose problème, mais la disconformité à 926,5 m dans le puits Mallik 2L-38 pourrait néanmoins correspondre à la discordance entre les sous-zones 4b et 4c de la Zone à Embryophyte de la coupe des collines Caribou ou, peut-être, à un intervalle quelconque au sein de la sous-zone 4c de cette même zone. En corrélation avec le puits Adgo F-28, la disconformité à 926,5 m dans le puits Mallik 2L-38 pourrait être corrélée avec le sommet de la Zone à *Integricorpus*. Cependant, *Integricorpus* ne présente pas d'occurrences abondantes et cohérentes dans sa zone d'extension. Par conséquent, l'identification de son niveau de dernière occurrence dans quelque étude peut poser problème, si bien que la corrélation résultante est incertaine.

Les paléochangements climatiques constituent un élément prédominant du Cénozoïque. Une approche paléoclimatique expérimentale permettant de préciser les datations consiste à corréler la série palynologique du puits Mallik à la courbe des valeurs de $\delta^{18}O$ pour les foraminifères de l'Atlantique Nord, qui sert de série de référence d'indicateurs indirects des paléotempératures. Les taxons de pollen dont les taxons contemporains apparentés montrent une sensibilité à la température servent à reconstituer des courbes expérimentales de températures relatives en calculant des rapports de taxons. Ces rapports sont distincts sur le plan statistique, mais à titre de produits expérimentaux, leur sensibilité ratios cannot be compared with others in the region because such ratios have not been calculated previously, nor are the required quantitative data available from other studies in the basin. Four ratios were calculated: thermophilous angiosperms/total angiosperms, (thermophilous angiosperms minus *Ulmus*)/total angiosperms, Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae, and *Pinus/Picea*. The *Pinus*/*Picea* ratio is less clearly in phase with the other ratios, but it and thermophilous angiosperms/total angiosperms show contemporaneous excursions near 950 m, showing that they are independently responding to some short-term environmental event recorded in the cored interval, the response apparently being by *Pinus* and *Ulmus*. The dominance of *Ulmus* amongst the thermophilous angiosperms is removed by calculating a (thermophilous angiosperms minus *Ulmus*)/total angiosperms ratio. This and Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae yield similar patterns and the two are taken as the prime proxies for paleotemperature. They jointly show a warm interval below and at 1000 m and suggest a long-term cooling event above that level to about 890 m. The two ratios suggest that a cold climatic episode coincided with the deposition of sediment at the top of the main gas-hydrate-hosting zone at 897 m. Using the biostratigraphic indicators as a temporal guide, this event is suggested to correlate with the basal Oligocene portion of the North Atlantic Ocean foraminiferal $\delta^{18}$O curve, with the *caveat* that resolution and the degree of smoothing in curves is critical for correlation, but are not controlled in this case. This proposed correlation suggests a relationship between the Early Oligocene cold event and the top of the interval where gas-hydrate deposits were subsequently emplaced. Any relationship must be indirect, perhaps through the climatic effect on sedimentation. Geophysical logs, which are dominated by the occurrence of gas hydrate, do not resolve this effect. The experimental paleotemperature proxy ratios are out of phase above 880 m and difficult to interpret.

The taxonomy of triprojectate pollens *Integricorpus* and *Parviprojectus* are considered and it is proposed to provisionally adopt '*Integricorpus* sp. cf. *I. reticulatus* of Parsons (2000)' for the reticulate form and retain usage of '*Parviprojectus* A of Rouse (1977)' for the striate form. A new, Late Eocene species of triprojectate pollen, *Striatocorpus sweetii*, is described from the Mallik 2L-38 well.

aux paléotempératures doit être étudiée davantage. On ne peut les comparer à d'autres rapports pour la région, car il n'en existe pas encore et les données quantitatives nécessaires ne figurent dans aucune autre étude sur le bassin. Quatre rapports ont été calculés : angiospermes thermophiles/angiospermes totaux, (angiospermes thermophiles à l'exception de *Ulmus*)/angiospermes totaux, Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae et *Pinus*/*Picea*. Le rapport *Pinus*/*Picea* est moins clairement en phase avec les autres rapports, mais celui-ci, ainsi que le rapport angiospermes thermophiles/angiospermes totaux présentent des excursions contemporaines de leurs courbes à près de 950 m, ce qui indique une réponse indépendante à un quelconque épisode environnemental de courte durée qui a laissé sa trace dans l'intervalle carotté, la réponse étant vraisemblablement rattachée à *Pinus* et à *Ulmus*. La prédominance d'*Ulmus* parmi les angiospermes thermophiles est éliminée en calculant le rapport (angiospermes thermophiles à l'exception de *Ulmus*)/angiospermes totaux. Ce rapport et le rapport Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae présentent des configurations similaires et sont considérés comme les principaux indicateurs indirects des paléotempératures. Ils rendent compte tous les deux d'un intervalle chaud à 1000 m et au-dessous, ce qui laisse croire qu'un épisode de refroidissement de longue durée a laissé sa trace au-dessus de ce niveau jusqu'à environ 890 m. Ces deux rapports laissent supposer qu'un épisode climatique froid a coïncidé avec le dépôt de sédiments au sommet de la principale zone d'hydrates de gaz naturel, à 897 m. En se fondant sur des indicateurs biostratigraphiques à des fins chronologiques, on peut supposer que cet événement est corrélé avec la base de l'intervalle oligocène de la courbe de $\delta^{18}$O pour les foraminifères de l'Atlantique Nord; il faut toutefois noter que la résolution et le degré de lissage des courbes est essentiel à cette corrélation, mais qu'ils n'ont pas été contrôlés dans le cas présent. Cette corrélation hypothétique évoque une relation entre l'événement froid de l'Oligocène précoce et le sommet de l'intervalle où des hydrates de gaz naturel ont ensuite été mis en place. Toute relation doit être de caractère indirect et pourrait résulter de l'effet du climat sur la sédimentation. Les diagraphies géophysiques ne permettent pas de bien cerner cet effet en raison du signal prédominant des occurrences d'hydrates de gaz. Les rapports indirects expérimentaux des paléotempératures ne sont pas en phase au-dessus de 880 m et sont difficiles à interpréter.

La taxinomie des pollens à trois projections *Integricorpus* et *Parviprojectus* est envisagée, et l'on propose de choisir '*Integricorpus* sp. cf. *I. reticulatus* de Parsons (2000)' comme forme réticulée et '*Parviprojectus* A de Rouse (1977)' comme forme striée. Une nouvelle espèce de pollen à trois projections datant de l'Éocène tardif, soit *Striatocorpus sweetii*, est décrite à partir de son occurrence dans le puits Mallik 2L-38.

# INTRODUCTION

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

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

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

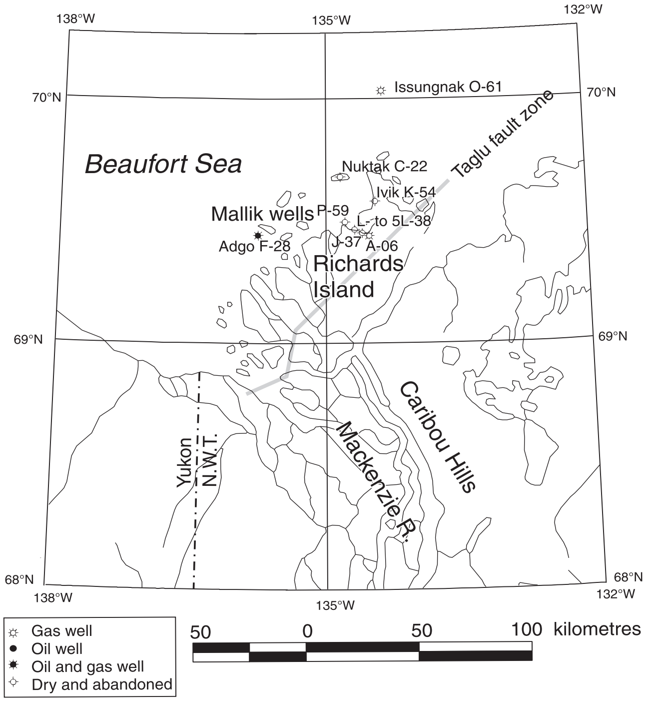


**Figure 1.** Location diagram.

For the study of the palynostratigraphy and paleoclimatology of the Beaufort-Mackenzie Basin, Mallik 2L-38 well provides an uncommon opportunity to analyze core and high-quality cuttings that span a 480 m section of upper Paleogene and Neogene sediment. The study should contribute to knowledge of the Late Eocene, and of the Oligocene, which is poorly known in northern Canada (Dixon et al., 1992). Likewise, the drilling program also provided a rare 7 m of core of Pliocene-Pleistocene sediment.

## Tectonic setting

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

## Sequences

Several sequence stratigraphic subdivisions have been proposed for the Mallik L-38 and 2L-38 wells (Fig. 2). Sequence tops for the original Mallik L-38 well have been determined by foraminifera by Dixon and Peach (1988), who recognized the Iperk and Kugmallit sequences within the 1150 m depth of the Mallik 2L-38 well. Based on regional geological correlations, log character, seismic profiles, and to some extent on paleontology, Dixon (1990) recognized a probable Mackenzie Bay Sequence in the upper portion of what Dixon and Peach (1988) called Kugmallit Sequence. Both schemes recognized the presence of the marine Richards Sequence at 1934 m in Mallik L-38 well, indicated by the occurrence of *Jadammina statuminis* (McNeil and Birchard, 1989).

For the Mallik 2L-38 study, Collett and Dallimore (1998) identified the Iperk, Mackenzie Bay, and Kugmallit sequences, differing chiefly from previously cited studies by the 932 m pick for the top of the Kugmallit Sequence. After sedimentological study of the Mallik 2L-38 core, Jenner et

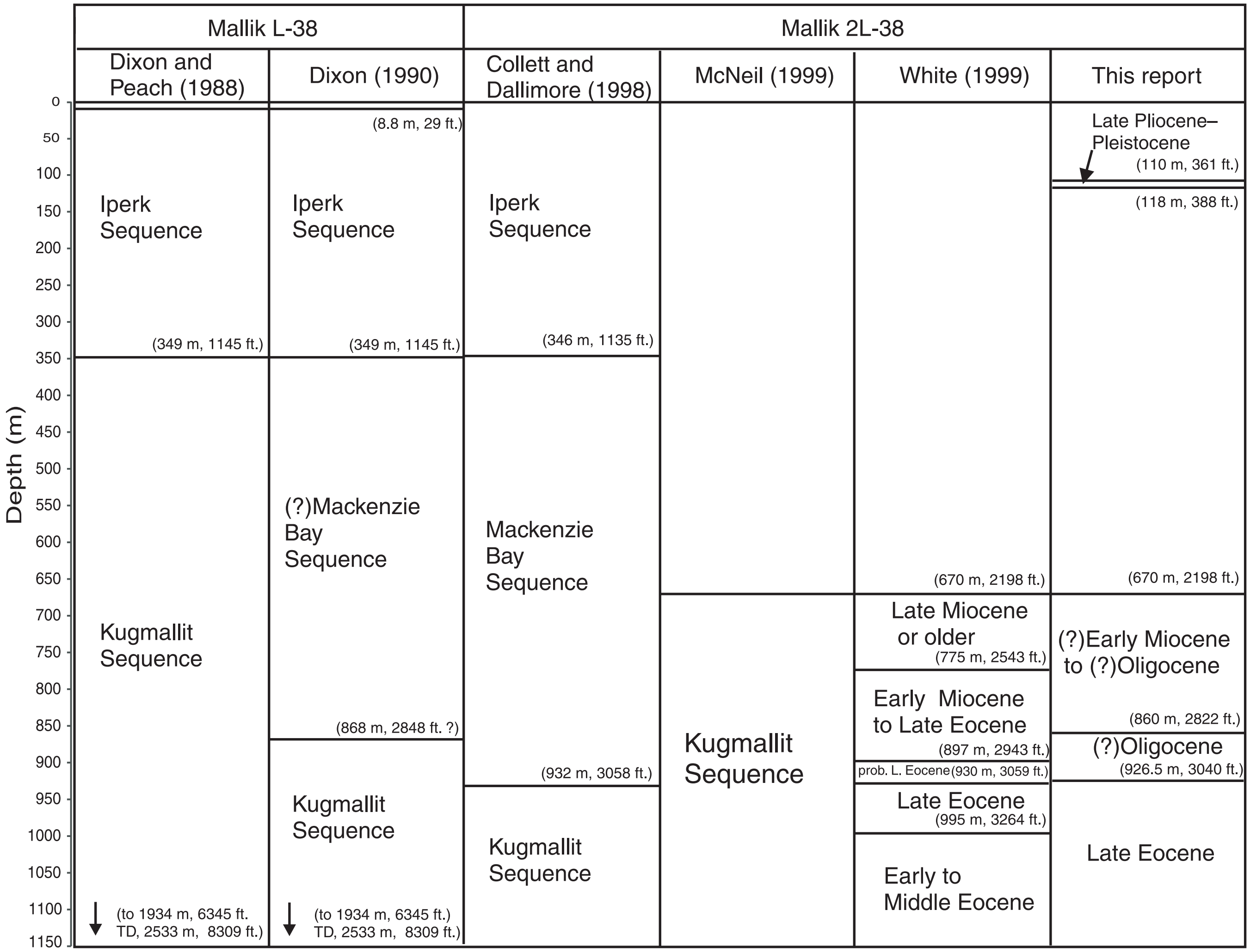


**Figure 2.** Sequence names and age determinations applied previously and by this report to Mallik L-38 and Mallik 2L-38 wells; prob. = probably; TD = total depth.

al. (1999) tentatively placed the Mackenzie Bay–Kugmallit sequence contact in Mallik 2L-38 well at 926.5 m, referred to herein as a disconformity.

## Previous age interpretation and recycling

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

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

White (1999) recognized recycled pollen, spores, and dinoflagellates, but argued that the in situ pollen and spores provided a primary biostratigraphic signal, and proposed an age interpretation for the section below 995 m to be Early to Middle Eocene, from 995 m to 930 m to be Late Eocene, 930 m to 897 m to be probably Late Eocene, and 897 m to 670 m to be between Late Eocene and Late Miocene. Sequence affiliations that were suggested were based on the age determinations, using the stratigraphic shorthand assumption that an Oligocene age would indicate the Kugmallit Sequence, a Late Eocene age would indicate the Richards Sequence, and an Early to Middle Eocene age would indicate the upper Taglu and Richards sequences.

In the following discussion, White's (1999) age interpretation is revised, such that all sediment from 670 m to 926.5 m is considered to be probably Early Miocene–Oligocene, and sediment below 926.5 m to total depth is considered to be Late Eocene. The biostratigraphy is presented quantitatively and it is argued by biostratigraphic and statistical arguments that the palynomorph record provides a primary palynostratigraphic signal, in spite of some recycling. This bulletin is similar to Open File 5088 (White, 2006), but includes plates of the palynomorphs.

## Lithology of Mallik 2L-38 well

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

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

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

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

# METHODS

## Drilling and palynological sampling

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

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

## Curation of materials

Samples of cuttings and core used in this study, and palynological slides that do not contain holotypes or figured specimens are stored at the Geological Survey of Canada, Calgary, 3303–33rd Street NW, Calgary. Slides containing holotypes or figured specimens are stored temporarily in the Palynological Type Collection at GSC Calgary, and their permanent repository will be the Paleontological Type Collection at the Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario.

## Palynological analysis

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

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

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

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

Although sedimentological reports (Jenner et al., 1999) indicated the presence of some detrital coal in the 886–952 m core samples, only one sample (942.72–0.74 m) had a "?coal" note attached on the laboratory processing sheet (GSC Calgary palynological lab number P4364–27, curation number C-400730). Only a portion of the coal was broken down by the processing techniques used, so that palynomorphs from the possible coal would not have contributed much to the sample assemblage analyzed. No sample remained of P4367–27, so that the "?coal" residue cannot be remacerated separately to see its palynomorph content. Three supplementary samples of coal (928.95 m, 929.05 m, and 929.23 m) were obtained in March of 2000 after the original palynological analysis, to see if they might contribute to the resolution of the age of the sediment. These samples were scanned for useful taxa, which were recorded semiquantitatively. (The floras were not age diagnostic, with the exception of *Diervilla* of McIntyre, 1991 at 929.23 m.)

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

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

After the initial report (White, 1999), a systematic review of the palynoflora was conducted from top to bottom of the well, including the 886–952 m cored interval. Rare taxa recorded from all samples were reviewed and about 120 digital images taken of significant or unknown taxa. For consistency in identification, taxa were checked against previous occurrences. Sample records were updated as reanalysis and image capture proceeded. Some samples have been re-examined four times. Taxonomic review of identifications has resulted in some changes. Two significant taxa, recorded in White (1999, Table 1) as *Mancicorpus* sp. of Ridgway et al. 1995 and as *Parviprojectus* sp. were combined in this manuscript and named *Striatocorpus sweetii* n. sp. Also, changes were made in identification of 'unknowns', recorded here as 'Mallik2L-38 unknown *n*' (*see* below).

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

Norris' (1986, 1997) taxonomy has been generally followed because much of the comparative data has been derived from the Adgo F-28 well, for which Norris (1997) presented his latest palynostratigraphic zonation for the Cenozoic strata in the Beaufort-Mackenzie Basin. The Adgo F-28 well study was founded on previous work in the Nuktak C-22 well (Norris, 1986). Recently, Parsons and Norris (1999) and Parsons (2000) made significant contributions in the analysis of the palynostratigraphy and taxonomy of the Reindeer

Formation at the Caribou Hills sections. Parsons (2000) closely followed the taxonomy of Norris (1986, 1997). Thus, the taxonomic usage of Norris, of Parsons, and of this study are compatible, except for the use in this study of modern botanical names for taxa which can be referred to modern families, genera, and species (White and Ager, 1994). To record unidentified palynomorphs in StrataBugs, a pseudogenus and species designation is used here, i.e. 'Mallik2L-38 unknown *n*'. This designation permits unknown specimens to be attached uniquely to the Mallik 2L-38 well in a database and a formal binomial can be proposed subsequently for an unknown, without affecting the identifications of taxa from other studies.

Where it was useful to make a specific comparison of a fungal palynomorph, this study generally follows the taxonomy of Norris (1986, 1997) and W.C. Elsik's short course notes (palynology short course presented under the auspices of Louisiana State University at Baton Rouge, October 4–6, 1981). Subsequently, Kalgutkar and Jansonius (2000) comprehensively reviewed the taxonomy of fungal palynomorphs, resulting in the transfer in this manuscript of *Diporisporites pisciculatus* Norris 1997 to *Inapertisporites pisciculatus* (Norris) Kalgutkar and Jansonius 2000.

## Sums and concentration calculations

The palynomorph percentage diagram summation routines are designed to characterize the whole assemblage in terms of recycled, marine, and terrestrial (including lacustrine) components (Table 1). The percentages of these groups, and the individual taxa making them up are calculated as percentages of the 'sum of palynomorphs' (Fig. 3). Within this overall characterization of the assemblage, the taxa in 'terrestrial pollen and spores' are represented as a group (Fig. 4, on CD-ROM). Their percentages are calculated on the 'sum of terrestrial pollen and spores', to characterize the individual taxa and groups of taxa within the terrestrial component. The summation category into which each taxon was placed is in Table 1.

The estimate of the concentration of palynomorphs per gram of sediment is shown in Figure 5. Such plots have high variability, so the data are presented in a logarithmic plot.

## Criteria proposed to assess recycling

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

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

### *Randomness of distribution of rare taxa*

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

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

**Table 1.** Table of attributes of palynomorphs used in sums routines.

| Taxon | Group | Recycled | Dinoflagellates | Algae | Fungi | Bryophyte | Ferns and allies | Gymnosperms | Angiosperms | Temperate angiosperms |
|---|---|---|---|---|---|---|---|---|---|---|
| *Cymatiosphaera* sp. | AC | | | 1 | | | | | | |
| *Micrhystridium* group | AC | | | 1 | | | | | | |
| *Pterospermopsis* sp. | AC | 1 | | | | | | | | |
| *Sigmopollis carbonis* | AL | | | 1 | | | | | | |
| *Sigmopollis hispidus* | AL | | | 1 | | | | | | |
| *Sigmopollis* sp. | AL | | | 1 | | | | | | |
| *Botryococcus* sp. | AL | | | 1 | | | | | | |
| Algae spp. | AL | | | 1 | | | | | | |
| *Chatangiella ditissima* | DC | 1 | | | | | | | | |
| *Cleistosphaeridium* sp. | DC | 1 | | | | | | | | |
| *Deflandrea* sp. | DC | | 1 | | | | | | | |
| Dinoflagellate indet.(110.11 m) | DC | | 1 | | | | | | | |
| Dinoflagellate indet.( Not 110.11 m) | DC | 1 | | | | | | | | |
| *Habibacysta tectata* | DC | | 1 | | | | | | | |
| *Hystrichosphaeridium* sp. | DC | 1 | | | | | | | | |
| ?*Labyrinthodinium truncatum* | DC | | 1 | | | | | | | |
| *Lecaniella foveata* | DC | 1 | | | | | | | | |
| *Operculodinium* sp. | DC | | 1 | | | | | | | |
| *Spiniferites* sp. | DC | | 1 | | | | | | | |
| *Basidiosporites* sp. | FU | | | | 1 | | | | | |
| *Brachysporisporites* sp. | FU | | | | 1 | | | | | |
| *Desmidiospora* sp. | FU | | | | 1 | | | | | |
| *Diporicellaesporites* sp. | FU | | | | 1 | | | | | |
| *Inapertisporites pisciculatus* | FU | | | | 1 | | | | | |
| *Diporisporites* sp. | FU | | | | 1 | | | | | |
| *Dyadosporites* sp. | FU | | | | 1 | | | | | |
| *Foveodiporites* sp. | FU | | | | 1 | | | | | |
| *Fractisporonites* sp. | FU | | | | 1 | | | | | |
| Fungi hyphae | FU | | | | 1 | | | | | |
| Fungi hyphae type A of Norris (1986) | FU | | | | 1 | | | | | |
| *Hypoxylonites* sp. | FU | | | | 1 | | | | | |
| *Monoporisporites* sp. | FU | | | | 1 | | | | | |
| *Multicellaesporites* sp. | FU | | | | 1 | | | | | |
| *Pluricellaesporites* sp. | FU | | | | 1 | | | | | |
| *Polyadosporites* spp. | FU | | | | 1 | | | | | |
| *Striadiporites inflexus* | FU | | | | 1 | | | | | |
| *Abies* sp. | SP | | | | | | | 1 | | |
| *Acanthotriletes varispinosus* | SP | 1 | | | | | | | | |
| *Acer* sp. | SP | | | | | | | | 1 | 1 |
| *Aceripollenites tener* | SP | | | | | | | | 1 | 1 |
| *Alnus* four-porate | SP | | | | | | | | 1 | |
| *Alnus* five-porate | SP | | | | | | | | 1 | |
| *Alnus* six-porate | SP | | | | | | | | 1 | |
| *Anemia*-type | SP | | | | | | 1 | | | |
| *Annutriporites* sp. A of Norris (1986) | SP | | | | | | | | 1 | |
| Apiaceae undiff. | SP | | | | | | | | 1 | |
| *Aquilapollenites clarireticulatus* | SP | 1 | | | | | | | | |
| *Aquilapollenites magnus* | SP | 1 | | | | | | | | |
| *Aquilapollenites quadrilobus* | SP | 1 | | | | | | | | |
| *Aquilapollenites* sp. | SP | 1 | | | | | | | | |
| *Striatocorpus sweetii* | SP | | | | | | | | 1 | |
| *Aquilapollenites trialatus* | SP | 1 | | | | | | | | |
| *Aquilapollenites unicus* | SP | 1 | | | | | | | | |
| *Artemisia* sp. | SP | | | | | | | | 1 | |
| *Baculatisporites comaumensis* | SP | | | | | | 1 | | | |
| *Baculatisporites crassiprimarius* | SP | | | | | | 1 | | | |
| *Baculatisporites primarius primarius* | SP | | | | | | 1 | | | |
| *Baculatisporites quintus* | SP | | | | | | 1 | | | |
| *Betula* ≤ 20 um | SP | | | | | | | | 1 | |
| *Betula* >20 um | SP | | | | | | | | 1 | |
| *Boehlensipollis hohli* | SP | | | | | | | | 1 | |
| *Boisduvalia clavatites* | SP | | | | | | | | 1 | |
| Brassicaceae undiff. | SP | | | | | | | | 1 | |
| Caprifoliaceae undiff. | SP | | | | | | | | 1 | |
| *Carya* sp. | SP | | | | | | | | 1 | 1 |
| Caryophyllaceae undiff. | SP | | | | | | | | 1 | |
| *Castanea*-type | SP | | | | | | | | 1 | 1 |
| *Cedrus* sp. | SP | | | | | | | 1 | | |
| Chenopodiineae undiff. | SP | | | | | | | | 1 | |
| *Cibotiumspora jurienensis* | SP | | | | | | 1 | | | |
| *Cicatricosisporites augustus* | SP | 1 | | | | | | | | |
| *Cicatricosisporites australiensis* | SP | 1 | | | | | | | | |
| *Cicatricosisporites paradorogensis* | SP | | | | | | 1 | | | |
| *Cicatricosisporites* sp. | SP | 1 | | | | | | | | |
| *Classopollis classoides* | SP | 1 | | | | | | | | |
| *Concavisporites* sp. | SP | | | | | | 1 | | | |
| *Cornus* sp. | SP | | | | | | | | 1 | |
| *Cornus stolonifera*-type | SP | | | | | | | | 1 | |
| *Corylus*-type | SP | | | | | | | | 1 | |
| *Cristatisporites orcadensis* | SP | 1 | | | | | | | | |
| Cyperaceae undiff. | SP | | | | | | | | 1 | |
| *Deltoidospora* sp. | SP | | | | | | 1 | | | |
| *Densosporites rarispinosus* | SP | 1 | | | | | | | | |
| *Diervilla echinata* | SP | | | | | | | | 1 | |
| Droseraceae undiff. | SP | | | | | | | | 1 | |
| *Ephedra* sp. | SP | | | | | | | 1 | | |
| *Equisetum* sp. | SP | | | | | | 1 | | | |
| Ericales undiff. | SP | | | | | | | | 1 | |
| *Fagus* sp. | SP | | | | | | | | 1 | 1 |
| *Foveosporites* sp. | SP | | | | | | 1 | | | |
| *Fraxinus* sp. | SP | | | | | | | | 1 | 1 |
| *Gleicheniidites senonicus* | SP | 1 | | | | | | | | |
| *Gothanipollis* sp. | SP | | | | | | | | 1 | |
| *Ilex*-type | SP | | | | | | | | 1 | 1 |
| *Impardecispora apiverrucata* | SP | 1 | | | | | | | | |
| *Impardecispora marylandensis* | SP | 1 | | | | | | | | |
| *Impardecispora minor* | SP | 1 | | | | | | | | |
| *Integricorpus* sp., cf. *I. reticulatus* | SP | | | | | | | | 1 | |
| Iridaceae or Liliaceae undiff. | SP | | | | | | | | 1 | |
| *Juglans* sp. | SP | | | | | | | | 1 | 1 |
| *Jussiaeae* (*Ludwigia*) sp. | SP | | | | | | | | 1 | 1 |
| *Labrapollis* sp. | SP | | | | | | | | 1 | |
| *Laevigatosporites* sp. | SP | | | | | | 1 | | | |
| *Larix- or Pseudotsuga*-type | SP | | | | | | | 1 | | |
| *Osmunda irregulites*? | SP | | | | | | 1 | | | |
| *Liquidambar* sp. | SP | | | | | | | | 1 | 1 |
| *Lonicerapollis gallwitzii* | SP | | | | | | | | 1 | |
| *Lycopodium inundatum* | SP | | | | | | 1 | | | |

AC = acritarch

AL = alga

DC = dinoflagellate

FU = fungus

SP = spore or pollen

**Table 1.** (cont.)

| Taxon | Group | Recycled | Dinoflagellates | Algae | Fungi | Bryophyte | Ferns and allies | Gymnosperms | Angiosperms | Temperate angiosperms |
|---|---|---|---|---|---|---|---|---|---|---|
| *Lycopodium selago* | SP | | | | | | 1 | | | |
| *Lycopodium* sp. | SP | | | | | | 1 | | | |
| ***Lycopodium* spike** | **SP** | | | | | | | | | |
| *Lycopodiumsporites marginatus* | SP | 1 | | | | | | | | |
| *Magnolia* sp. | SP | | | | | | | | 1 | 1 |
| Mallik2L-38 unknown 01 | SP | | | | | 1 | | | | |
| Mallik2L-38 unknown 02 | FU | | | | 1 | | | | | |
| Mallik2L-38 unknown 03 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 04 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 05 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 06 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 07 | SP | | | 1 | | | | | | |
| Mallik2L-38 unknown 08 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 09 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 10 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 11 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 12 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 13 | FU | | | | 1 | | | | | |
| Mallik2L-38 unknown 14 | SP | | | | | | 1 | | | |
| Mallik2L-38 unknown 15 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 16 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 17 | SP | | | | | | 1 | | | |
| Mallik2L-38 unknown 18 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 19 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 20 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 21 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 22 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 23 | SP | | | | | | | 1 | | |
| Mallik2L-38 unknown 24 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 25 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 26 | FU | | | | 1 | | | | | |
| Mallik2L-38 unknown 27 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 28 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 29 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 30 | SP | | | | | | | | 1 | |
| Mallik2L-38 unknown 31 | SP | | | | | | | | 1 | |
| *Momipites wyomingensis*? | SP | | | | | | | | 1 | |
| *Murospora* sp. | SP | 1 | | | | | | | | |
| *Nyssa*? sp. | SP | | | | | | | | 1 | 1 |
| *Osmunda regalis* | SP | | | | | | 1 | | | |
| *Osmunda* sp. | SP | | | | | | 1 | | | |
| *Osmundacidites wellmanii* | SP | | | | | | 1 | | | |
| *Ostrya or Carpinus* sp. | SP | | | | | | | | 1 | 1 |
| *Ovoidites ligneolus* | SP | | | 1 | | | | | | |
| *Paraalnipollenites alterniporus* | SP | | | | | | | | 1 | |
| *Parviprojectus* A of Rouse (1977) | SP | | | | | | | | 1 | |
| *Picea* sp. | SP | | | | | | | 1 | | |
| *Picea* sp. (robust corpus) | SP | | | | | | | 1 | | |
| *Picea* sp. (small) | SP | | | | | | | 1 | | |
| Pinaceae undiff. | SP | | | | | | | 1 | | |
| *Pinus* (robust corpus) | SP | | | | | | | 1 | | |
| *Pinus koraiensis*-type | SP | | | | | | | 1 | | |
| *Pinus* sp. | SP | | | | | | | 1 | | |
| *Pistillipollenites macgregorii* | SP | | | | | | | | 1 | |
| cf. *Planera* sp. | SP | | | | | | | | 1 | 1 |
| Poaceae undiff. | SP | | | | | | | | 1 | |
| *Podocarpus*-type | SP | | | | | | | 1 | | |
| Polypodiaceae or Dennstaedtiaceae | SP | | | | | | 1 | | | |
| *Polyvestibulopollenites trinus* | SP | | | | | | | | 1 | |
| *Pristinuspollenites microsaccus* | SP | 1 | | | | | | | | |
| *Pristinuspollenites pannosus* | SP | 1 | | | | | | | | |
| *Psilastephanocolpites* sp. cf. *P. marginatus* of Norris (1997) | SP | | | | | | | | 1 | |
| *Pterocarya* sp. | SP | | | | | | | | 1 | 1 |
| *Quercus* sp. | SP | | | | | | | | 1 | 1 |
| Recycled palynomorphs | SP | 1 | | | | | | | | |
| *Retimonocolpites excelsus* | SP | 1 | | | | | | | | |
| *Retitricolpites* sp. | SP | | | | | | | | 1 | |
| *Retitriletes* sp. | SP | | | | | | 1 | | | |
| *Retitriletes* sp. cf. *R. novomexicanus* of Norris (1986) | SP | | | | | | 1 | | | |
| *Rhoipites* sp. cf. *R. microreticulatus* of Norris (1997) | SP | | | | | | | | 1 | |
| *Rhoipites* sp. | SP | | | | | | | | 1 | |
| *Ribes* sp. | SP | | | | | | | | 1 | |
| Rosaceae undiff. | SP | | | | | | | | 1 | |
| *Rugubivesiculites* sp. | SP | 1 | | | | | | | | |
| *Salix* sp. | SP | | | | | | | | 1 | |
| *Schizosporis reticulatus* | SP | | | 1 | | | | | | |
| *Sciadopitys* sp. | SP | | | | | | | 1 | | |
| *Selaginella selaginoides* | SP | | | | | | 1 | | | |
| *Shepherdia canadensis* | SP | | | | | | | | 1 | |
| *Sparganium* sp. | SP | | | | | | | | 1 | |
| *Sphagnum* sp. | SP | | | | | 1 | | | | |
| *Stereisporites microgranulus* | SP | | | | | 1 | | | | |
| *Striatocorpus sweetii* sp. nov. | SP | | | | | | | 1 | | |
| Taxodiaceae-Cupressaceae-Taxaceae undiff. | SP | | | | | | | 1 | | |
| Tetrad pollen (scabrate) | SP | | | | | | | | 1 | |
| Tetraporate spp. | SP | | | | | | | | 1 | |
| *Tilia*-type | SP | | | | | | | | 1 | 1 |
| *Tricolpites* sp. | SP | | | | | | | | 1 | |
| *Tricolporopollenites* sp. | SP | | | | | | | | 1 | |
| *Trilobosporites* sp. | SP | 1 | | | | | | | | |
| *Tripartites incisotrilobus* | SP | 1 | | | | | | | | |
| *Diervilla* of McIntyre (1991) | SP | | | | | | | | 1 | |
| *Triporopollenites* sp. | SP | | | | | | | | 1 | |
| *Trudopollis* sp., *T. barentsii?* | SP | | | | | | | | 1 | |
| *Tsuga canadensis*-type | SP | | | | | | | 1 | | |
| *Tsuga heterophylla*-type | SP | | | | | | | 1 | | |
| *Tsuga* sp. | SP | | | | | | | 1 | | |
| Tubuliflorae undiff. | SP | | | | | | | | 1 | |
| *Ulmus*-type | SP | | | | | | | | 1 | 1 |
| Unknown and undeterminable spp. | SP | | | | | | | | | |
| *Verrucatosporites favus* | SP | | | | | | 1 | | | |
| *Vitreisporites pallidus* | SP | 1 | | | | | | | | |
| *Wodehouseia spinata* | SP | 1 | | | | | | | | |

AC = acritarch

AL = alga

DC = dinoflagellate

FU = fungus

SP = spore or pollen

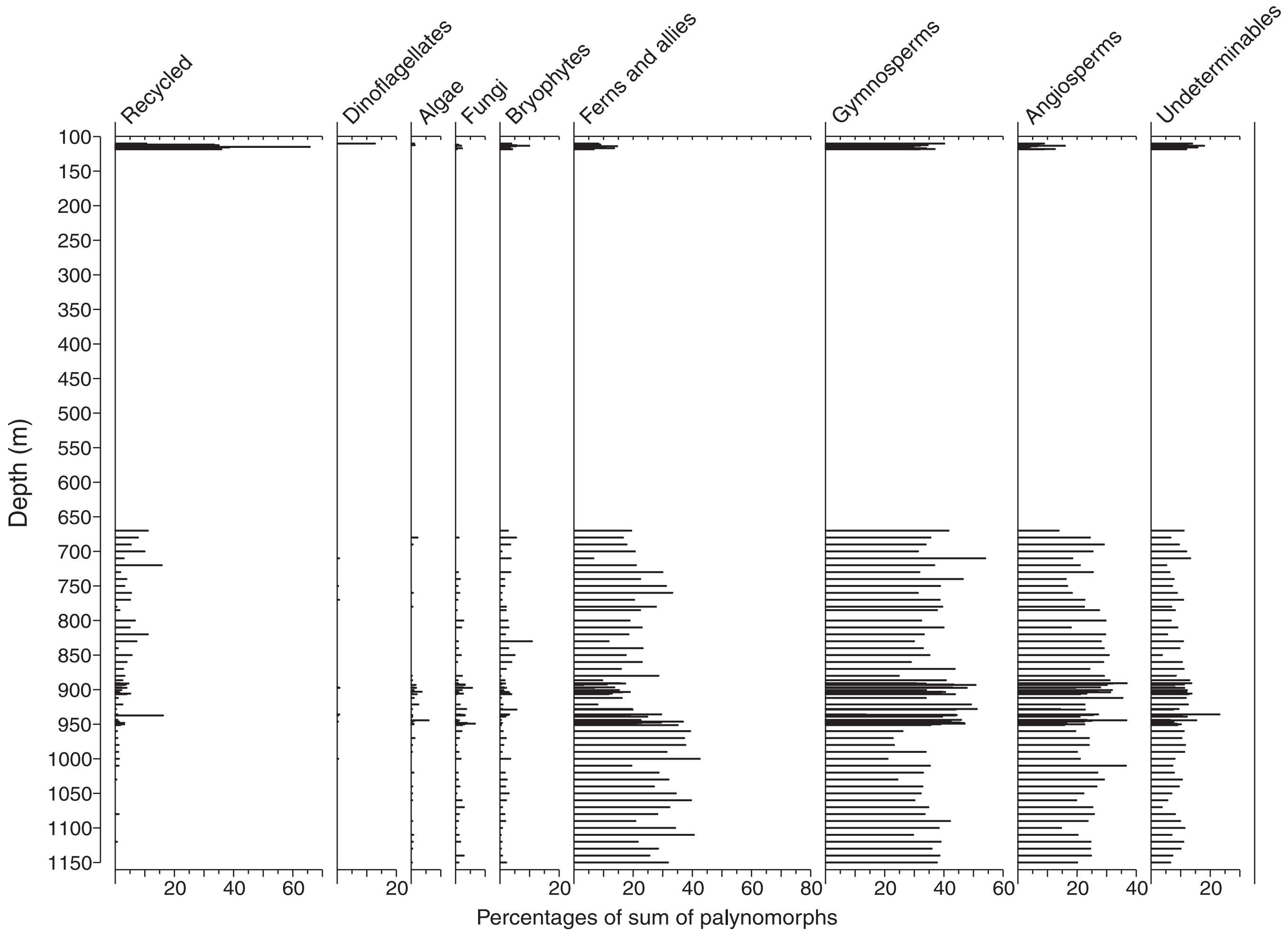


**Figure 3.** Percentages of major groups in the sum of palynomorphs: recycled, dinoflagellates, algae, fungi, bryophytes, ferns and allies, gymnosperms, angiosperms, and undeterminables.

# RESULTS AND INTERPRETATION

## Overview

A total of 16 108 palynomorphs and 220 taxa were identified and tallied during the palynological analysis (count per sample: $\bar{x}$ = 194.07, s = 73.96, minimum 19 (at 720 m), maximum 299 (at 1120 m)). In the interval of cores 12 to 24, palynomorph sums range from 63 to 316 specimens per sample.

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

The focus of this paper and following discussion is on the strata penetrated by the well between 670 m to 1150 m. As discussed above, identification of the ages of rocks and sequences penetrated by the Mallik 2L-38 well is contentious. This disagreement between continental and marine biostratigraphic results is a useful opportunity to consider and clarify the differences to the benefit of biostratigraphy and to the interpretation of regional geology. The following discussion describes the palynological results from the Mallik 2L-38 well, and demonstrates that patterns exist that argue against recycling as the primary signal in the palynological record. It considers correlation and age assignment for several intervals, necessitating a consideration of the taxonomy of some triprojectate pollen found in northern Paleogene rocks. It considers correlation options to other surface and subsurface sections, and the age constraints of the foraminiferal *Haplophragmoides richardsensis* Zone and the *H. richardsensis* Zone in the Mallik L-38 well. It considers existing paleoclimatic evidence for the Eocene-Oligocene boundary and derives paleoclimatic interpretations from palynological

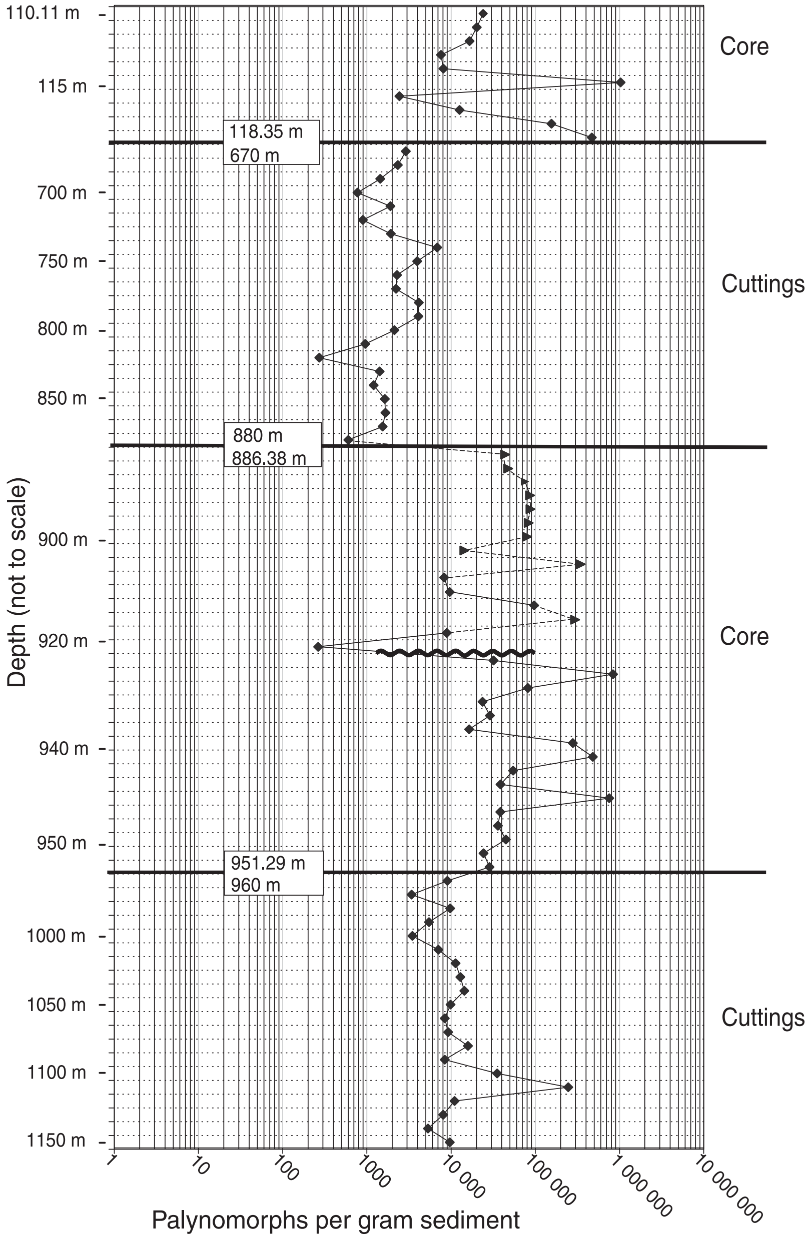


**Figure 5.** Concentration of palynomorphs/gram of sediment. The samples shown as triangles are those for which the sample weight and exotic *Lycopodium* addition was estimated.

count data from Mallik 2L-38 well, uses the paleoclimatic results to compare with the North Atlantic Ocean $\delta^{18}$O paleoclimatic record to refine the age interpretation, and compares the interpretations to regional tectonic patterns.

(Figures 3, 4, and 7 show stratigraphic distributions of individual taxa and taxa groups. Not all taxa are plotted, but occurrences are listed in count sheets for each sample in Appendix D.)

## Palynology, correlation, and age in the 111–670 m interval

### *110.11–118.35 m, Late Pliocene–Pleistocene*

Figure 4c shows the distribution of palynomorphs in samples 111.12 m to 118.34 m in cores 1 and 2. Cyperaceae, *Artemisia*, Tubuliflorae, and Poaceae occur commonly in this interval. The first three do not occur lower in the well, and the last does not occur below 690 m. *Sphagnum* is more abundant that in the underlying intervals. Total gymnosperms are also more abundant, made up chiefly of *Picea* and secondarily *Pinus*.

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

*Artemisia*, present, but not abundant in this interval, argues for an age in the Late Pliocene to Pleistocene (White et al., 1999). On the other hand, the abundance of Taxodiaceae-Cupressaceae-Taxaceae pollen in this interval (Fig. 4a) suggests an older, Pliocene age, probably the middle Pliocene warm interval (Dowsett et al., 1994; White et al., 1999). Inasmuch as there is abundant Cretaceous recycling in this interval (Fig. 6), and Taxodiaceae-Cupressaceae-Taxaceae pollen is abundant in Cretaceous and Paleogene rocks, recycled specimens could have contributed to the Taxodiaceae-Cupressaceae-Taxaceae sum. Thus, it seems best to give more weight to the presence of *Artemisia.* A study of the adjacent Mallik 5L-38 well (J.M. White, work in progress, 2008) shows evidence of glaciation occurring between 340 m and 270 m. Significant northern hemisphere glaciation began about 2.75 Ma (Shackleton et al., 1984; Flesche Kleiven et al., 2002), so this interval is probably Late Pliocene to Pleistocene.

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

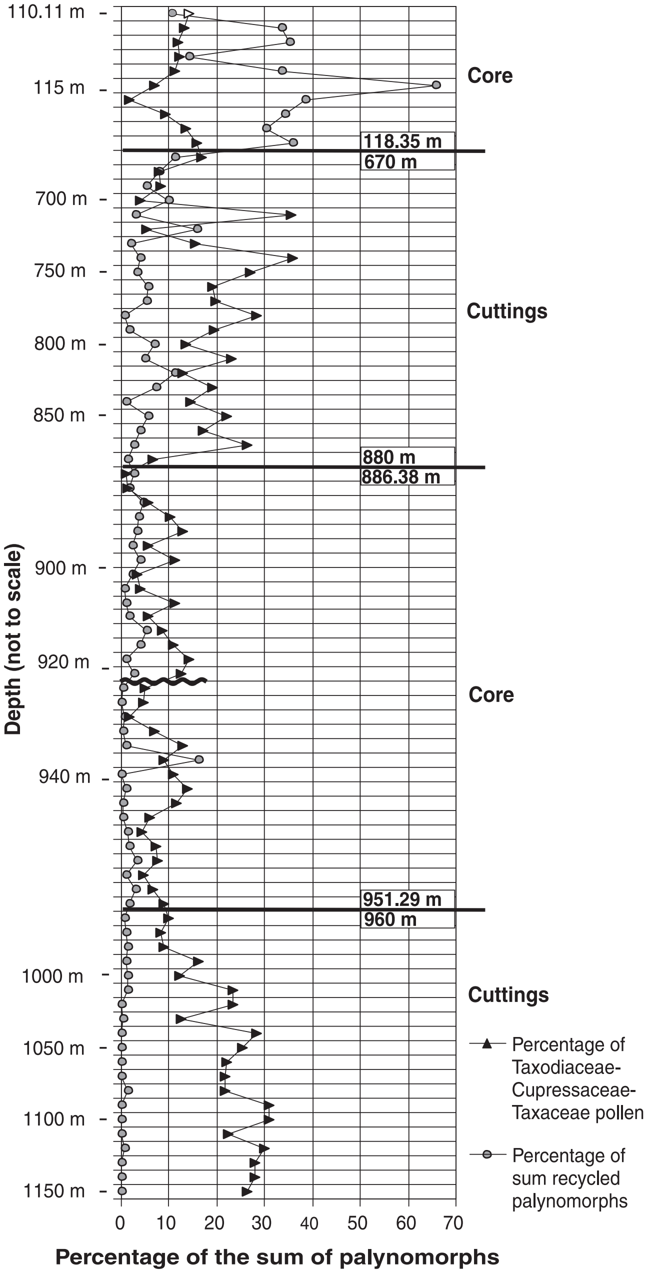


**Figure 6.** Taxodiaceae-Cupressaceae-Taxaceae pollen versus total recycled palynomorphs.

The great abundance of recycled palynomorphs in cores 1 and 2 (Fig. 3) is a response to increased erosion and sedimentation rates in the Pliocene and Pleisotocene, which may be due to increased climatic oscillation (Peizhen et al., 2001) or to regional tectonic activity.

### *118–670 m, unknown*

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

## Palynological results and the evaluation of recycling in the 670–1150 m interval

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

### *Concentration estimates of palynomorphs*

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

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

Three patterns are immediately apparent (Fig. 5). In the intervals where the data were derived from core samples there is much higher variability than in the intervals where data were derived from cuttings. This high variability in pollen concentration and influx measurements is typical of palynological results from late Quaternary sediments (e.g. White and Mathewes, 1986), in which palynological samples are taken of very short sediment increments. The averaging effect of samples taken over 10 m increments, rather than 2 cm increments, likely explains the lower concentration variability of the cutting samples. Another obvious pattern is that the concentration of palynomorphs per gram in the core samples is about an order of magnitude higher than in the cutting samples. This is due to the acquisition of core samples from only organic-rich intervals. It is also apparent that the samples from the lower cutting interval (1150–960 m) have a concentration some three or four times higher that the samples from the upper cutting interval (880–670 m). This consistent pattern must be due to fundamental differences in biological productivity or sedimentation rate, or both.

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

## *Patterns of terrestrial pollen and spore assemblages*

Figure 4a shows, for the whole well, the percentages of individual taxa of terrestrial pollen and spores, and totals for the groups; fungi, bryophytes, ferns and fern allies, gymnosperms, and angiosperms. Figure 4b shows the percentages of terrestrial pollen and spores for the 886–952 m core interval, which cannot be shown clearly on the Figure 4a because the samples are at much closer intervals than for the rest of the well. Percentages are based on the sum of terrestrial pollen and spores in order to represent changes that occurred within the terrestrial plant community.

### Pollen percentages in core versus cuttings

Figure 4a shows that there is a significant increase in Taxodiaceae-Cupressaceae-Taxaceae percentage abundance and a decline among the Pinaceae across the transition from the uppermost core sample at 886.38 m to the overlying cutting sample at 880 m.

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

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

### General features of percentage distributions

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

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

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

### *Fungi*

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

## *Ferns and fern allies*

*Laevigatosporites* sp. and *Deltoidospora* sp. are more abundant below 928 m than above (Fig. 4). This transition occurs across the 926.5 m sequence boundary proposed by Jenner et al. (1999). The core-to-cutting change has no effect on the *Laevigatosporites* percentages.

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

## *Gymnosperms*

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

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

Taxodiaceae-Cupressaceae-Taxaceae pollen are both abundant and long ranging at high latitude, occur in strata from the Cretaceous to the late Neogene, and could be readily recycled from older strata. To assess potential recycling, Figure 6 shows a plot of Taxodiaceae-Cupressaceae-Taxaceae and total recycled palynomorphs, both calculated as percentages of the sum of palynomorphs. Figure 6 is unscaled to depth so that points in the core interval are not vertically compressed. There is no similarity in percentage pattern of these curves, arguing that the Taxodiaceae-Cupressaceae-Taxaceae category is not dominated by pollen recycled from Cretaceous strata.

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

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

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

## *Angiosperms*

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

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

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

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

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

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

*Ulmus*-type pollen (White and Ager, 1994) occurs regularly with intervals of reduced abundance in the middle of the cored interval and absence below the cored interval at about 1050 m. Above the core, it occurs consistently, except for an absence between 720 m and 760 m.

### *Recycled, dinoflagellates, algae, and undeterminable categories*

Figure 7 illustrates the relative abundance of palynomorphs in three categories: recycled palynomorphs, dinoflagellates, and algae. The percentages of all taxa in this diagram are calculated on the sum of all palynomorphs, representing their abundance as a percentage of the whole assemblage.

'Recycled palynomorphs' includes those that can be determined to species and a category of undetermined recycled palynomorphs. This latter category includes taxa that are badly preserved and not clearly identifiable, but are most likely recycled. Discretely identifiable recycled specimens are relatively rare compared to the undetermined specimens. The recycled palynomorphs abundance is high between 110 m and 118 m, indicating a time of active erosion, and conversely, recycled palynomorphs are very rare below 1010 m. Otherwise, recycled palynomorphs are generally less than 5% of the assemblage.

The identified recycled palynomorphs indicate the recycling of older rocks into strata penetrated by the Mallik 2L-38 well. *Aquilapollenites* spp. and *Chatangiella ditissima* (McIntyre) Lentin and Williams 1976, indicate recycling from Santonian to Maastrichtian strata (Lentin and Williams, 1993; Nichols and Sweet, 1993). *Wodehouseia spinata* Stanley 1961 is indicative of recycling from the late Maastrichtian to the earliest Paleocene (Nichols and Sweet, 1993). *Cicatricosisporites* spp., *Gleicheniidites senonicus* Ross 1949, *Pristinuspollenites* spp., *Rugubivesiculites* sp., *Trilobosporites* sp., and *Vitreisporites pallidus* (Reisinger) Nilsson 1958 indicate recycling from Early to mid-Cretaceous rocks (Burden and Hills, 1989). *Densosporites rarispinosus* Playford 1963 is recycled from Lower Carboniferous rocks (J. Utting, pers. comm., 2000-03-03). There is little clustering in the distribution of identifiable recycled taxa, but there is a small cluster of Cretaceous taxa in the 948.16 m to 937.36 m interval.

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

## *Runs test of the distribution of rare taxa*

Table 2 shows the results of the runs test of the significance of distribution of rare taxa. The results are sorted from low to high probabilities. Twelve taxa, from Mallik2L-38 unknown 06 to *Striadiporites inflexis*, have probabilities associated with their distributions of less than 0.01. Taxa from *Aceripollenites tener* to *Magnolia* sp. have probabilities less than 0.05, and *Striatocorpus sweetii* and *Tilia*-type have associated probabilities less than 0.1. Thus, one may conclude that 17 taxa show patterns of distribution which are extremely to somewhat unlikely to be caused by random chance, and the $H_o$ for those taxa may credibly be rejected. The negative $z$ scores indicate fewer runs than would be expected by random chance, i.e. that some other factor, likely biological or environmental, is influencing the distribution.

It can be justifiably argued that the greater intensity of sampling in core versus cuttings results in a greater probability of runs of presences occurring in the core interval, and absences in the cuttings. To assess this problem, the taxa are coded as to whether they occur in core, cutting, or in both. Of the taxa with low probability distributions, eight occur only in the cutting samples, spread over various stratigraphic levels, i.e. *Foveosporites* sp., *Lonicerapollis gallwitzii*, Mallik2L-38 unknown 06, *Retritiletes* sp. cf. *R. novomexicanus* of Norris, *Verrucatosporites favus*, *Striadiporites inflexus*, *Stereisporites microgranulus*, and *Striatocorpus sweetii*. Three taxa occur exclusively in the core interval, i.e. Mallik2L-38 unknown 25, *Ovoidites lignoleus*, and *Podocarpus*-type. Six taxa occur in core and cuttings, i.e. *Quercus* sp., *Fagus* sp., *Labrapollis* sp., *Aceripollenties tener*, *Magnolia* sp., and *Tilia*-type. (A reappraisal of *L. gallwitzii* records concluded that the occurrences in core at 897.36 m and 903.01 m are questionable, perhaps being pollen of other Caprifoliaceae species, whereas those between 1110 m and 1150 m are reliable. Thus the probability that the observed distribution is random is smaller than shown in Table 2.) Inspection of Figure 4a shows that these nonrandomly distributed rare taxa are found throughout the 670–1150 m interval, suggesting that nonrandom pattern of occurrences are not determined by clustering factors associated with any specific part of the sequence. In other words, there is no specific part of the 670–1150 m interval that shows patterned occurrences, whereas other parts show random occurrence. Various taxa have stratigraphic occurrence patterns that are apparently biologically driven and that occur throughout the 670–1150 m interval. If the

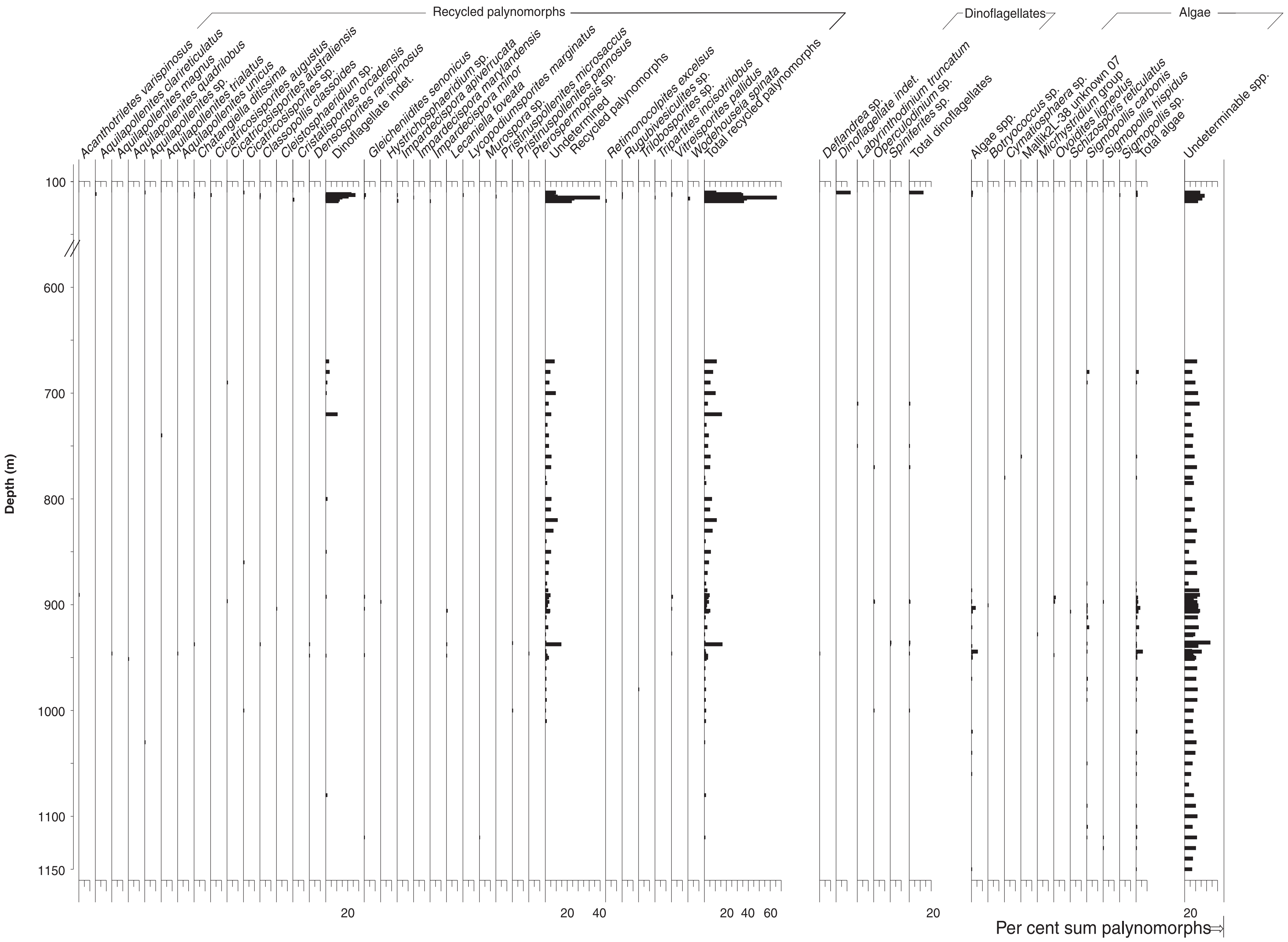


**Figure 7.** Recycled palynomorphs, dinoflagellates, algae, and undeterminable taxa from the Mallik 2L-38 well (analyzed by J.M. White, December 1999).

proposed criterion of a nonrandom pattern of occurrence assists in separating palynomorph occurrences showing biological patterns versus one dominated by recycled palynomorphs, the patterned occurrences, shown above, argue against recycling as a useful explanation of palynomorph distributions in the Mallik 2L-38 strata, 670–1150 m interval. Comparison of the scores with Figure 4a shows that the test of runs is particularly sensitive to contiguous occurrences of the selected taxa; however, other taxa among the original 38 chosen have some distinct patterns of clustering to which a test of runs is not sensitive. A long interval of absence of a taxon (e.g. in *Cicatricosisporites paradorogensis*) constitutes just one run. Although that pattern of presence and absence intuitively appears significant, this is not resolved by the runs test.

**Table 2.** Wald-Wolfowitz test of randomness of occurrence of rare taxa, calculated by Systat 5.02. The occurrence pattern of the rare taxa is commonly 1 or 0, so 0.5 was chosen as a discriminator (cut) to separate the taxa into runs. The $H_o$ is that the occurrences of presences and absences shown by each of the selected taxa is not different from a random pattern. The negative z scores indicate fewer runs than would be expected by random chance ( – occurs in cuttings, • - occurs in core).

| Cases < cut | Cases > cut | Runs | Z | Probability (two-tailed) | Palynomorph |
|---|---|---|---|---|---|
| *71* | *2* | *3* | *-4.783* | *<0.001* | Mallik2L-38 unknown 06 ♦ |
| *71* | *2* | *3* | *-4.783* | *<0.001* | Mallik2L-38 unknown 25 • |
| *69* | *4* | *5* | *-4.290* | *<0.001* | *Ovoidites ligneolus* • |
| 67 | 6 | 7 | -4.051 | <0.001 | *Podocarpus*-type • |
| 61 | 12 | 12 | -3.930 | <0.001 | *Quercus* sp. ♦• |
| 61 | 12 | 8 | -5.667 | <0.001 | *Retitriletes* sp. cf. *R. novomexicanus* of Norris ♦ |
| 67 | 6 | 8 | -3.243 | 0.001 | *Lonicerapollis gallwitzii* ♦• |
| 66 | 7 | 9 | -3.253 | 0.001 | *Verrucatosporites favus* ♦ |
| 63 | 10 | 12 | -3.171 | 0.002 | *Fagus* sp. ♦• |
| 63 | 10 | 12 | -3.171 | 0.002 | *Labrapollis* sp. ♦• |
| 70 | 3 | 5 | -2.845 | 0.004 | *Foveosporites* sp. ♦ |
| 70 | 3 | 5 | -2.845 | 0.004 | *Striadiporites inflexus* ♦ |
| 67 | 6 | 9 | -2.435 | 0.015 | *Aceripollenites tener* ♦• |
| 67 | 6 | 9 | -2.435 | 0.015 | *Stereisporites microgranulus* ♦ |
| 50 | 23 | 25 | -2.055 | 0.040 | *Magnolia* sp. ♦• |
| 69 | 4 | 7 | -1.881 | 0.060 | *Striatocorpus sweetii* ♦ |
| 61 | 12 | 17 | -1.760 | 0.078 | *Tilia*-type ♦• |
| 59 | 14 | 20 | -1.392 | 0.164 | *Tsuga heterophylla* -type ♦• |
| 70 | 3 | 6 | -1.222 | 0.222 | *Liquidambar* sp.• |
| 66 | 7 | 12 | -1.158 | 0.247 | *Paraalnipollenites alterniporus* ♦• |
| 65 | 8 | 17 | 1.083 | 0.279 | *Jussiaeae* (*Ludwigia*) sp. ♦• |
| 61 | 12 | 23 | 0.844 | 0.398 | *Carya* sp. ♦• |
| 68 | 5 | 11 | 0.660 | 0.509 | *Castanea*-type ♦• |
| 68 | 5 | 11 | 0.660 | 0.509 | *Juglans* sp. ♦ |
| 60 | 13 | 21 | -0.557 | 0.577 | Mallik2L-38 unknown 12 ♦• |
| 69 | 4 | 9 | 0.528 | 0.597 | Apiaceae ♦• |
| 69 | 4 | 9 | 0.528 | 0.597 | *Ilex*-type • |
| 69 | 4 | 9 | 0.528 | 0.597 | *Rhoipites sp.* cf. *microreticulatus* of Norris 1997 ♦ |
| 70 | 3 | 7 | 0.400 | 0.689 | *Cicatricosisporites paradorogensis* ♦ |
| 70 | 3 | 7 | 0.400 | 0.689 | *Integricorpus* sp. cf. *I. reticulatus* of Parsons (2000) ♦ |
| 71 | 2 | 5 | 0.277 | 0.782 | Mallik2L-38 unknown 09 ♦• |
| 71 | 2 | 5 | 0.277 | 0.782 | Mallik2L-38 unknown 19 ♦• |
| 71 | 2 | 5 | 0.277 | 0.782 | *Psilastephanocolpites sp.* cf. *marginatus* of Norris 1997 ♦ |
| 72 | 1 | 3 | 0.168 | 0.867 | *Boisduvalia clavatites* ♦ |
| 72 | 1 | 3 | 0.168 | 0.867 | *Diervilla echinata* ♦ |
| 72 | 1 | 3 | 0.168 | 0.867 | *Parviprojectus* A of Rouse 1977 ♦ |
| 72 | 1 | 3 | 0.168 | 0.867 | *Pistillipollenites macgregorii* ♦ |

### *Balance of evidence regarding recycling*

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

## Correlation and age

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

### *670–860 m, (?) Early Miocene–(?)Oligocene*

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

As the age constraints for the 670–775 m interval are not definitive, the same possibilities must be considered for the 775–860 m interval. Within the Neogene, *Liquidambar* has been proposed as a Middle Miocene indicator (White et al., 1999). *Liquidambar* occurs at 830 m in Mallik 2L-38 well, but it also does not co-occur with the rich assemblage of thermophilous angiosperms typical of the warm interval (White and Ager, 1994; White et al., 1999). *Tilia*-type underlies *Liquidambar* at 860 m and 850 m, and *Ilex*-type, *Castanea*–type, and *Fagus* occur above *Liquidambar*, between 800 m and 780 m. A Middle Miocene age also seems unlikely for this interval, even though the dispersed distribution of thermophilous taxa might be due to the relatively low palynomorph sums (54–110 grains per sample) in the stratigraphic interval from 800 m to 850 m.

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

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

## *860–926.5 m, Oligocene*

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

## *926.5–1150 m, Late Eocene*

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

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

- A consideration of the age and environment of deposition of dinoflagellates identified by Kurita and Uchida (1999) in core samples from 926.2 m and 948.1 m.
- A discussion of the taxonomy of the triprojectate pollen *Integricorpus* and *Parviprojectus*, which are important for correlation in the Paleogene.
- A discussion of possible correlations between Mallik 2L-38 well and the Caribou Hills sections.
- A correlation of Mallik 2L-38 well to Adgo F-28 well by last appearance data.
- A consideration of the biostratigraphic ranges of indicators found in Mallik 2L-38 well, but not in the Caribou Hills sections or in Paleogene–early Neogene sections of Adgo F-28 or Nuktak C-22 wells.
- An identification of a possible disconformity within this sedimentary interval at 1000 m.

### *Dinoflagellates from 945.21 m and 948.16 m*

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

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

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

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

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

## Integricorpus-Parviprojectus *taxonomy*

The triprojectate pollen *Integricorpus* sp. A has figured prominently in correlations proposed by Norris (1986, 1997) as the nominate species for a palynostratigraphic zone. The discussion below provisionally establishes taxonomic relationships for correlation, although Paleogene triprojectate pollen requires more comprehensive taxonomic treatment (Parsons et al., 2001).

This discussion recommends that the *Integricorpus* species found in Mallik 2L-38 well, Adgo F-28 well, and the Caribou Hills sections be accepted as the same species. The name "*Integricorpus* sp. cf. *I. reticulatus* (Mtchedlishvili) Stanley 1970," as used in Parsons (2000), is adopted in this study. The above species is distinguished from *Integricorpus* sp. A of Norris (1986), and from *Parviprojectus* sp. PJ-1 of Staplin (1976), *Parviprojectus* A of Rouse (1977) and

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

| **Mallik 2L-38 taxa** (Kurita and Uchida, 1999) | **Taglu Sequence, Natserk E-56,** (Dietrich et al., 1989) | **Taglu Sequence, Caribou Hills** (Parsons, 2000) | **Chronostratigraphic range** (Willams et al., 1993 or Williams et al. 1998) |
|---|---|---|---|
| *Apectodinium homomorphum* | *Apectodinium homomorphum* | *Apectodinium homomorphum* | Early to Middle Eocene (55–41 Ma) |
| *Cordosphaeridium fibrospinosum* | | | Cretaceous to Early Oligocene (33 Ma) |
| *Deflandrea* sp. ind. | Contains a *Deflandrea* | Deflandreoid dinoflagellates | Late Early Cretaceous to Neogene |
| *Glaphyrocysta divaricata* | *Galphyrocysta divaricata* | *Glaphyrocysta divaricata/pastielsii* | Early Eocene |
| *Glaphyrocysta exubarens* | | | Early to Late Eocene (54–38 Ma) |
| *Hystrichokolpoma*? sp. | | *Hystrichokolpoma reticulatum* and species | Late Cretaceous to Neogene |
| *Lentinia serrata* | | | Late Middle to Late Eocene (43–37 Ma) |
| *Spiniferites* sp. cf. *pseudofurcatus* | | *Spiniferites* spp. | Cretaceous to Late Miocene (10.2 Ma) |

Rouse and Mathews (1979), and *Parviprojectus* sp. A of Marincovich and Wiggins (1990) and Ridgway et al. (1995). This *Integricorpus* sp. A and these several *Parviprojectus* specimens are either the same species or a closely related lineage, for which the name *Parviprojectus* A of Rouse (1977) is used herein.

In retrospect, it was an error for Norris (1997) to apply the name *"Integricorpus* sp. A Norris" to a triprojectate specimen found in Adgo F-28 well (Norris, 1997, Pl. 5, fig. 19–21), therein referring it to a triprojectate found in Nuktak C-22 well (Norris, 1986, Pl. 9, fig. 12–14). In this discussion, the specimens are distinguished. The Nuktak C-22 specimen is referred to *Parviprojectus* A of Rouse (1977). The Adgo F-28 specimen should be referred to *Integricorpus* sp. cf. *I. reticulatus* (Mtchedlishvili) Stanley 1970 illustrated by Parsons (2000, p. 508, Pl. 7, fig. 4, 5, 7, 12, 14) from the Caribou Hills sections.

## Integricorpus

Parsons (2000) noted the similarity between the Adgo F-28 well and the Caribou Hills specimens, but separated them because the "cf. *I. reticulatus"* specimens are wider, have colpi extending onto the body of the grain, have more pronounced equatorial protrusions, and a coarser, stronger reticulum; however, Parsons now considers the Caribou Hills sections and the Adgo F-28 well specimens to be the same species (M.G. Parsons, pers. comm., 2001-05-03). Adgo F-28 specimens of *Integricorpus* sp. A of Norris 1997 (Norris, 1997, Pl. 5, fig. 19–21) exhibit a large size range (polar and equatorial size, 28–36 µm and 10–18 µm, respectively) with equatorial projection 4–13 µm long. The exine has a very notable angular reticulum over the grain, coarser at the equator than at the poles, with a mesh diameter up to 1 µm at the equator. The reticulum also extends onto the projections, although finer than on the body of the grain.

White (1999) called the Mallik 2L-38 specimens *Integricorpus* sp. A of Norris (1986), following the name applied by Norris (1997) to his Adgo F-28 well triprojectate. In this revised study, these specimens are called *Integricorpus* sp. cf *I. reticulatus* (Mtchedlishvili) Stanley 1970, following Parsons (2000). The three specimens from Mallik 2L-38 well occur between 936.32 m and 950.11 m, the lowest specimen being poorly preserved. They are triprojectate grains with a subangular microreticulum (*see* Pl. 5, fig. 18a, b, 19a, b). On the projections the ornament becomes finely strio-reticulate to very faintly reticulate to scabrate distally. The Mallik 2L-38 specimens are similar to those illustrated by Norris (1997, Pl. 5, fig. 19–21) and Parsons (2000). The Mallik specimens' polar axes are within 30–33 µm, similar to the 28–36 µm range of specimens shown by Norris (1997) and the 24–34 µm range of Parsons (2000, p. 508). The width of the Mallik specimens is 12–14 µm, within the 10–18 µm range of Norris' (1997) illustrations, and Parsons' (2000) 12–26 µm range. The equatorial projections in Mallik 2L-38 specimens are obliquely presented, but are measured at 8 µm, within the range of 7–14 µm described by Parsons' (2000).

Thus, the *Integricorpus* specimens in the Caribou Hills sections, Adgo F-28 well, and Mallik 2L-38 well are the same species, recognizable primarily by the coarse, subangular reticulum. Parsons' (2000) name, *Integricorpus* sp. cf. *I. reticulatus* is accepted here because the name *Integricorpus* sp. A used by Norris (1986, 1997) is considered to encompass two related species, as discussed above. In the Caribou Hills sections, the last occurrence datum of *I.* sp. cf. *I. reticulatus* is just below the top of the CHE4b subzone, considered to be Middle Eocene (Parsons, 2000), whereas in Adgo F-28 well, the last occurrence datum places it at the top of the Oligocene Kugmallit Formation (Norris, 1997; McNeil, Appendix A).

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

## Parviprojectus

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

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

Norris' specimens of "*Integricorpus* sp. A" from Nuktak C-22 well (Norris, 1986, Pl. 9, fig. 12–14) are stored at GSC Calgary; their poor preservation is evident in the figures. In size, they are 29–32 µm by 11–13 µm. The arms are too eroded for measurement or good observation of any detail, but one projection is about 3 µm long. The specimens have an infrareticulum that is so fine it is just barely visible, and at a higher focus there is a faint, polar-oriented striation, which is visible from pole to pole on the specimen illustrated in Norris' (1986) Figure 13, except the equatorial areas that are too eroded to determine the orientation of the striae. This is apparently the same species as *Parviprojectus* A, and not the same as *Integricorpus* sp. cf. *I. reticulatus* of the Adgo F-28 well (Norris, 1997).

In Nuktak C-22 well (Norris, 1986), *Parviprojectus* A (*Integricorpus* sp. A) has a last occurrence datum of 8800 ft. (2682.24 m), well below the last occurrence datum of *Haplophragmoides richardsensis* McNeil 1997 (=*Haplophragmoides* sp. 2000) at 6920 ft. (2109.22 m) (McNeil and Birchard, 1989) so that it occurs in the lower half of the Richards and in the upper Reindeer sequences, which would give a late Middle Eocene to early Late Eocene age (McNeil, 1997), which could span ca. 40–36 Ma by the Berggren et al. (1995) time scale. McNeil and Birchard (1989) gave a minimum 36.6 Ma age for *Haplophragmoides richardsensis*, which is terminal Eocene or older using the Berggren et al. (1985) time scale. (The Berggren et al. (1995) time scale revises the Eocene-Oligocene boundary to 33.7 Ma.) This is a minimum estimate of the older age range of *Parviprojectus* A, and other data suggest that its range is higher in the stratigraphic column (below).

Ridgway et al. (1995, Fig. 13G) illustrated a specimen of *Parviprojectus* sp. A, which is large (36 µm x 24 µm) with 4 µm projections, probably eroded at the tip. The ornament is strongly striate, and there is a faint microreticulum beneath the striations. The striations are longitudinally oriented from pole to pole, but some merge together at the equator and deflect in a direction parallel to the equator. At the equator there is a zone around the base of each projection in which the striae are approximately parallel to the equator and faint striations radiate out onto the projections. This is the best illustration of the specimens discussed here, which are subsumed under *Parviprojectus* A. *Parviprojectus* occurs in Ridgway et al.'s (1995) Oligocene biozone 2 (Ridgway et al., 1995).

Ridgway et al. (1995) noted that their *Parviprojectus* sp. A is the same as that cited by Marincovitch and Wiggins (1990) from lower Oligocene of Unga Island, Alaska. An unpublished photograph of Marincovich and Wiggins' specimen (photographs sent to A.R. Sweet by V.D. Wiggins, 1991) shows it to be similar in shape, with striate ornament and a zone of equatorially oriented striate around each projection, from which striae radiate out onto the projection. At Unga Island, *Parviprojectus* sp. A occurs in rocks that by radiometric estimate are younger than 31.3 ± 0.3 Ma.

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

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

One specimen of cf. *Parviprojectus* A of Rouse 1977 occurs in Mallik 2L-38 well. It is 27 µm x 14 µm, infrareticulate and faintly striate. It occurs at 936.21 m (Pl. 5, fig. 20a, b), in the sample with the last occurrence datum of *Integricorpus* sp. cf. *I. reticulatus*, showing that the stratigraphic ranges of *Integricorpus* sp. cf. *I. reticulatus* and *Parviprojectus* A overlap, at least in part. Although the correlation between the *Integricorpus* zones of Nuktak C-22 and Adgo F-28 wells is uncertain because they may be based on different species, the co-occurrence of these two taxa in core in Mallik 2L-38 well indicates that the *Integricorpus* zones of Nuktak C-22 and Adgo F-28 wells are penecontemporaneous.

### *Summary*

In summary, *Parviprojectus* A of Rouse 1977 includes triprojectate specimens that have a very fine infrareticulum and longitudinally oriented striae. The details of surface ornament cannot be compared for all specimens, but if not the same species, it is likely part of a closely related lineage. Considering the ages in Nuktak C-22 well and Unga Island samples, one must accept a stratigraphic range from the Eocene to the Early Oligocene. The distinctly reticulate species, *Integricorpus* sp. cf. *I. reticulatus* (Mtchedlishvili) Stanley 1970 ranges at least from late Middle Eocene to the Early Oligocene. The co-occurrence of both taxa in Mallik 2L-38 well at 936.32 m confirms that their ranges overlap. *Parviprojectus* A probably has the younger range extension of the two taxa.

## *Correlation of Mallik 2L-38 well to the Caribou Hills sections*

Caribou Hills, on the eastern margin of the Mackenzie Delta (Fig. 1), exposes a long series of Paleogene outcrop sections. They were described palynologically by Ioannides and McIntyre (1980), and recently in consummate detail by Parsons and Norris (1999) and Parsons (2000). Between the Late Paleocene and the (?) Late Eocene-Oligocene, Parsons and Norris (1999) and Parsons (2000) identified seven fungus zones (CHF1–CHF7), five algal zones (CHA1–CHA5), and four embryophyte zones (CHE1–CHE4), the uppermost being divided onto three subzones (CHE4a–CHE4c). Her data indicated the presence of the Taglu Sequence in Caribou Hills, a southward revision of the limits of the Taglu Sequence as depicted in Dixon (1996).

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

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

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

The most obvious correlation is suggested by the characteristic species *Integricorpus* sp. cf. *I. reticulatus* (*see* '*Integricorpus-Parviprojectus* taxonomy', above). In Mallik 2L-38 well it is found in the 936.32–950.11 m interval, and in the Caribou Hills sections as high as sample CH-90-6-12 in upper subzone CHE4b. In both cases, the last occurrence datum of *Integricorpus* is below a sedimentary hiatus, which in Mallik 2L-38 well occurs at 926.5 m and in the Caribou Hills sections occurs between subzones CHE4b and CHE4c (Parsons, 2000). This proposed correlation is supported by sedimentological interpretation of the change of depositional environment across the unconformity or disconformity, i.e. interpreted to be from a marsh–shallow marine lower delta plain environment to a fluvial environment in Mallik 2L-38 well (Jenner et al., 1999; *see also* Medioli et al., 2005), and from delta plain and occasional marine sedimentation to fluvial-lacustrine in the Caribou Hills sections (Price et al., 1980); however, the implication of a correlation based on *Integricorpus*, using Parsons' (2000) age determinations from Caribou Hills sections, would be that the strata below 926.5 m in Mallik 2L-38 well are Middle Eocene.

Moreover, testing the correlation based on *Integricorpus* by patterns in other taxa leads to more questions about the validity this correlation. Chiefly, *Juglanspollenites* spp. and *Quercoidiites* spp. are relatively abundant and occur consistently, yielding a better sense of their local biostratigraphic range, and they do not support the *Integricorpus* correlation. They occur in both subzones CHE4b and CHE4c, both below and above *Integricorpus*. In Mallik 2L-38 well they occur only below the *Integricorpus* last occurrence datum, *Juglans* below 990 m and *Quercoidites* below 1000 m (although the latter has single counts at 928.01 m and 905.74 m). *Accuratipollis? bitriangularis*, which occurs commonly in the CHE4b subzone (although possibly in a slump block in samples CH-90-6-46 to CH-90-6-49; G. Parsons, pers. comm., 2004-01-29), and rarely in upper subzone CHE4c assemblage is lacking in Mallik 2L-38 well. *Striatocorpus sweetii* occurs four times below 990 m in Mallik 2L-38 well, but no similar grain is recorded in subzone CHE4b or subzone CHE4c. *Pistillipollenites macgregorii* occurs commonly in subzone CHE4b and above the unconformity in subzone CHE4c, but in Mallik 2L-38 well, below the disconformity, only two specimens occur in the 1000 m sample. Relatively rare taxa, *Aceripollenites tener* and *Boisduvalia clavatites* occur rarely above and below the unconformity in the Caribou Hills sections (the latter possibly in a slump block in sample CH-90-6-46; G. Parsons, pers. comm., 2004-01-29), but occur only below the disconformity in Mallik 2L-38 well. Their occurrences are insufficiently consistent in one or the other sections for secure comparisons. *Magnolia magnolioides* appears once at the top of subzone CHE4c, but appears below the disconformity in the Mallik 2L-38 well (as *Magnolia* sp.). Thus, the most straightforward correlation based on *Integricorpus* appears to be seriously flawed.

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

Either correlation, aligning *Integricorpus*, or Mallik 2L-38 strata below 926.5 m to uppermost subzone CHE4b and the subzone CHE4b-CHE4c unconformity, implies a Middle Eocene age for Mallik 2L-38 strata, contrary to McNeil and Birchard's (1989) lower limit of late Middle to Late Eocene for Mallik 2L-38 strata, based on foraminifera from Mallik L-38 well. This could only be resolved if the uppermost part of subzone CHE4b were late Eocene or younger. This is contradicted by the occurrence of *Wetzeliella articulata* and *Charlesdowniea tenuivirgula* in sample CH-90-6-15, at the top of subzone CHE4b, unless these taxa are responding not just to time, but to environmental factors such as hyposalinity (e.g. Downie et al., 1971).

The correlation to the Caribou Hills sections is fraught with problems; the simplest and most obvious correlation, based on *Integricorpus*, may be wrong. What seems clear is that the Mallik 2L-38 strata correlate to uppermost subzone CHE4b or above; and this requires some extension of the range of *Integricorpus* sp. cf. *I. reticulatus* above its limits recorded in subzone CHE4b. How Mallik 2L-38 well and subzone CHE4c strata interfinger is a conundrum. Of the Late Eocene–Oligocene age proposed by Parsons (2000) for subzone CHE4c, the Late Eocene is preferred here, inasmuch as it retains the range of *Pistillipollenites macgregorii* within the Eocene. There is clearly much more to be discovered about palynostratigraphic ranges in northern Canada. The likely synonymy of *Acuratipollis*? *bitriangularis* and *Pseudolaesopollis* spp. (of Ridgway et al., 1995; Long and Sweet, 1994) (G. Parsons and A. Sweet, pers. comm., 2004-01-30) and their relationship with *Striatocorpus sweetii* are problems that need consideration. The outcome may shed light on this correlation problem.

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

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

Since the publication of the palynology of the Adgo F-28 well by Norris (1997), McNeil (Appendix A) has revised the formational (sequence) stratigraphy of the Adgo F-28 well (Fig. 8), based on re-examination of the foraminifera. There is now a definite recognition of a thin Kugmallit Formation in an interval that was formerly questionably assigned to the Mackenzie Bay–(?)Kugmallit sequences (McNeil and Birchard, 1989) or to the upper Richards Sequence (Norris, 1997). McNeil (Appendix A) noted that the top and base of the Kugmallit Formation are poorly defined on logs, but estimated them at 2800 ft. (853.4 m) and 3000 ft. (914.4 m), respectively, with a well defined base of the Richards Formation at 3360 ft. (1024.1 m). McNeil's new determination confirms Dixon's and Norris' identification of Richards Formation (*in* Norris, 1997), which underlies the Kugmallit Formation; however, for correlation and age determination, a significant feature of this revision is that Norris' (1997) and McNeil's (Appendix A) interpretations of the top of the Richards Sequence differ; Norris (1997) placed a Richards–Mackenzie Bay sequence contact at 2805 ft. (855 m) so the top of his *Integricorpus* Zone (2800 ft., 853.4 m), falls within the Richards Sequence (ignoring the 5 ft. (1.5 m) difference). In contrast, McNeil's recognition of the Kugmallit Formation (Appendix A) places the top of Norris' *Integricorpus* Zone in the Kugmallit Formation.

A cautious approach to the comparison of Adgo F-28 and Mallik 2L-38 stratigraphic sequences requires comparison by last appearance data. Mallik 2L-38 well is a scientific borehole, drilled with chilled mud to minimize caving (Ohara et al., 1999), and this study assumes that the palynomorphs found in cuttings are generally in place, and not recycled or caved (although caving is possible and some recycling of Cretaceous palynomorphs can be demonstrated). On the other hand, the Adgo F-28 well is an industrial borehole in which caving is more likely to extend the range of taxa downhole, although Norris (1997) indicated that in some intervals the palynostratigraphic data seem to be well constrained. This study has generally followed the taxonomy of Norris (1986, 1997), so comparison between the Mallik 2L-38 and the Adgo F-28 wells is facilitated.

A perfect alignment of last occurrence datums is unlikely because of stochastic considerations and environmental constraints on taxa. It is also possible that a last occurrence datum is due to an erosional truncation within a taxon's range, as opposed to being a biological event. Clearly, a last occurrence datum in a sequence of almost continuous occurrences is more meaningful than a 'last occurrence datum', constituting one occurrence (e.g. *Pistillipollenites macgregorii* in Mallik 2L-38 well). The stratigraphic resolution between the two studies differs. In Adgo F-28 well, cuttings average 100 ft. (30.5 m) of strata, whereas in the Mallik 2L-38 well, resolution is at 10 m intervals in the cuttings, and at metre- to centimetre-scale in cored intervals. Thus, last occurrence data that differ in Mallik 2L-38 well may be lumped into one interval in Adgo F-28 well.

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

A comparison of the last occurrence data between Adgo F-28 (Norris, 1977) and Mallik 2L-38 wells is as follows (Fig. 8).

The last occurrence datum of *Lonicerapollis gallwitzii* Krutzsch 1962 in the Mallik 2L-38 well is at 1110 m (two higher occurrences are questionable), and at 2300 ft. (701 m) in the Adgo F-28 well.

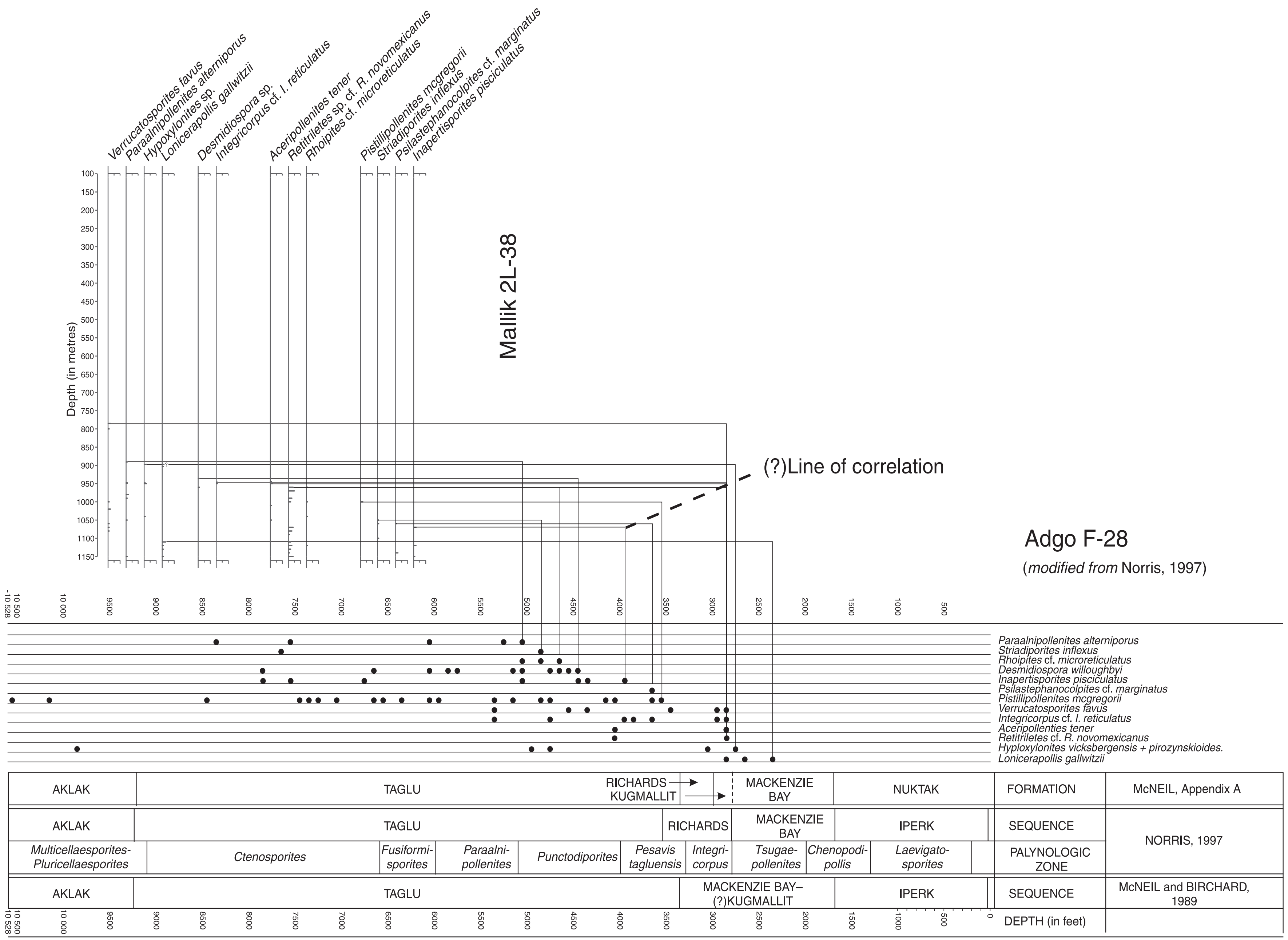


**Figure 8.** Graphic correlation style comparison of palynostratigraphy between Mallik 2L-38 well (this paper) and Adgo F-28 well (Norris, 1997).

The distinctive, but morphologically simple fungal spore *Hypoxylonites* has been given a generic identification in the Mallik 2L-38 well, where the last occurrence datum is at 897.36 m, above the *Integricorpus* last occurrence datum. In Adgo F-28 well, the last occurrence datum of *Hypoxylonites pirozynskioides* is at 2700 ft. (823 m), above *Integricorpus* sp. A.

The last occurrence datum of *Retitriletes* sp. cf. *R. novomexicanus* (Anderson) Norris 1986 occurs in Mallik 2L-38 well at 960 m and Adgo F-28 well at 2800 ft. (853.4 m).

The last occurrence datum of the distinctive *Integricorpus* sp. cf. *I. reticulatus* occurs in Mallik 2L-38 well at 936.32 m, just below the disconformity at 926.5 m. In Adgo F-28 well, the last occurrence datum is at 2800 ft. (853.4 m).

The last occurrence datum of *Aceripollenites tener* (Samoilovitch) Norris 1986 in Mallik 2L-38 well is 944.32 m, whereas in Adgo F-28 well, at lower stratigraphic resolution, it is contemporaneous with the last occurrence datum of *Integricorpus* at 2800 ft. (853.4 m).

The last occurrence datum of *Verrucatosporites favus* occurs in Mallik 2L-28 well at 785 m, and in Adgo F-28 well at 2800 ft. (853.4 m).

Two specimens of *Pistillipollenites macgregorii* Rouse 1962, generally considered an Early to Middle Eocene indicator (Rouse, 1977), were found in Mallik 2L-38 well at 1000 m near coaly beds, but no specimens were found below this level. Its last occurrence datum in Adgo F-28 well is 3500 ft. (1067 m) (Norris, 1997), in the uppermost Taglu–basal Richards sequence. In Adgo F-28 well, *P. macgregorii* occurs in the *Pesavis tagluensis* zone, but *P. tagluensis* was not observed in the Mallik 2L-38 well.

The last occurrence datum of *Psilastephanocolpites* cf. *marginatus* of Norris in Mallik 2L-38 well is at 1060 m and in Adgo F-28 well at 3600 ft. (1097.3 m).

The last occurrence datum of the probable fungal spore *Inapertisporites (Diporisporites) pisciculatus* in Mallik 2L-38 well is at 1070 m and in Adgo F-28 well at 3900 ft. (1188.7 m).

*Desmidiospora*, a fungal palynomorph, assigned generically in Mallik 2L-38 well, occurs at 935.78 m, and in Adgo F-28 well at 4400 ft. (1341 m).

The last occurrence datum of *Rhoipites* cf. *R. microreticulatus* is at 960 m in Mallik 2L-38 well, and at 4600 ft. (1402 m) in Adgo F-28 well.

The last occurrence datum of the distinctive fungal taxon *Striadiporites inflexus* is at 1050 m in Mallik 2L-38 well, and at Adgo F-28 well at 4800 ft. (1463 m) (Norris, 1997).

*Paraalnipollenties alterniporus*, the nominate species for a palynological zone in the Taglu Sequence in Adgo F-28 well, has a last occurrence datum at 5000 ft. (1524 m) (Norris, 1997). In Mallik 2L-38 well, *P. alterniporus* has one occurrence as high as 890.7 m, but its interval of most common occurrence is at and below 947.61 m. This is above the *Pistillipollenites macgregorii* last occurrence datum, whereas in Adgo F-28 well, *Paraalnipollenties alterniporus* has a last occurrence datum 1700 ft. (518.2 m) below *Pistillipollenties macgregorii.* (Other evidence indicates that *Paraalnipollenties alterniporus* ranges upwards to the Late Eocene (Long and Sweet, 1994), rather than being restricted to the Late Paleocene (as *Paraalnipollenties confusus*), as indicated by Rouse (1977).)

In Adgo F-28 well at about 2700–2800 ft. (823–853.4 m) the last occurrence data of *Hypoxylonites* spp., *Retitriletes* cf. *R. novomexicanus*, *Aceripollenites tener*, and *Intergricorpus* cf. *I. reticulatus* occur in what is now assigned to be Kugmallit Formation. These four taxa have last occurrences in the 960–897 m range of Mallik 2L-38 well. This makes an argument for correlation of these last occurrence datum events, but must be balanced against the following information; these last occurrence data represent only four of the 12 taxa occurring at the 2800 ft. (853.4 m) top of the newly defined Kugmallit Formation in Adgo F-28 well (Norris, 1997) with an additional 11 last occurrence data within ±100 ft. (30.48 m) of this top. Also, there is a cluster of occurrences of taxa between 1150 m and 935.78 m in Mallik 2L-38 well with last occurrence datums between 5100 ft. and 3500 ft. (1774.8 m and 1066.8 m) in Adgo F-28 well, including *Striadiporites inflexus*, *Rhoipites* cf. *microreticulatus*, *Desmidiospora willoughbyi (Desmidiospora sp.)*, *Inapertisporites pisiculatus*, *Psilastephanocolpites* cf. *marginatus*, and *Pistillipollenites macgregorii*. If true last occurrence datums are in Adgo F-28 well, the Mallik occurrences must be at or below the Adgo occurrences. This latter interval is considered to be upper Taglu Sequence by Norris (1997) and upper Taglu Formation–lower Richards Formation by McNeil (Appendix A).

The discussion above, the dispersion of data on Figure 8, and the inability to drawing one unequivocal line of correlation that is supported by the last occurrence data underscores the difficulty of making a correlation between Eocene to Oligocene Mallik 2L-38 and Adgo F-28 strata, nor is a correlation obvious to taxa in the overlying Mackenzie Bay strata in Adgo F-28 well. Attempted correlations require arbitrary weighting of one species against another. Resolution of the problem might be offered by a more comprehensive species list and attention to rarefaction curves.

## Biostratigraphic indicators absent in the Caribou Hills sections and Adgo F-28 well

Several taxa not recorded in Nuktak C-22 or Adgo F-28 wells or in the Caribou Hills sections occur in Mallik 2L-38 well and range from Eocene to Oligocene. The occurrence of taxa identified previously in Europe is probably due to Early Eocene land bridges connecting Europe and Fennoscandia to Baffin and Ellesmere islands via Greenland (Tiffney, 1985).

The Canadian Arctic and Greenland record of these floral elements is limited. In their study of Cenozoic sequences in the Canadian Arctic and Greenland, Harrison et al. (1999) noted that "…most of the depositional record between the mid-Eocene and the mid-Pliocene is missing....," although a good record exists for the Labrador Shelf. This interval of time is well represented in strata of the Beaufort-Mackenzie Basin (Dixon, 1996).

*Striatocorpus sweetii* (990–1140 m) is a new species (Pl. 5, fig. 21, 22a, b, 23) (Appendix B). In White (1999) this species was recorded as both *Parviprojectus* sp. and as *Mancicorpus* sp. of Ridgway et al. (1995). In subsequent taxonomic review and discussion with A.R. Sweet, these specimens were combined under *S. sweetii* sp. nov. A.R. Sweet (pers. comm., 1999) considers this species to be an intermediate form, based on overall shape, between the heteropolar *Mancicorpus* and isopolar *Parviprojectus*. As a new species, its age significance is uncertain, but it is closely allied to triprojectate pollen of the late Eocene and Oligocene, including the likely synonymous *Acuratipollis*? *bitriangularis*, and *Pseudolaesopollis* spp. (above). *Striatocorpus sweetii* is named after A.R. Sweet for his career-long fascination with triprojectate pollen.

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

*Boehlensipollis hohli* Krutzsch 1962 (p. 272, Pl. III, fig. 18–30) (Pl. 5, fig. 17a, b) occurs in Mallik 2L-38 well at 1120 m. Krutzsch (1962) indicated a middle Oligocene age. A Palynodata, version 6.0 search, plotted by the technique of White and Jessop (2002) shows that it has been recorded in the Paleocene and Eocene, but its citation abundance increased in the Late Eocene, and Late Eocene to Oligocene is the portion of its stratigraphic range where it is most abundantly cited.

*Diervilla* of McIntyre (1991) is found in Mallik 2L-38 well in a supplementary coal sample at 929.23 m, 2.7 m below the 926.5 m lithological boundary, and at 945.21 m and 1140 m. This is a large triporate grain with baculate ornament, illustrated by McIntyre (1991, Pl. 4, fig. 1, 2) as *Diervilla*. In ornament, it is very similar to Triporate B of Piel (1971, p. 1914, Fig. 150), but the pores differ. The protruding, thickened, and colpoid pore morphology of this specimen is exhibited by *Ludwigia* of Onagraceae (Praglowski et al., 1983, Fig. 10, 11), and it seems that this pollen more likely belongs in Onagraceae than Caprifoliaceae, as indicated by the name *Diervilla*; however, the name, "*Diervilla* of McIntyre (1991)" is used to compare this specimen to his specimen. This specimen was illustrated from the Buchanan Lake Formation assemblage, northeast Axel Heiberg Island, considered to be Middle Eocene, although a Late Eocene age could not be discounted (McIntyre, 1991).

A specimen of *Trudopollis* (Pl. 5, fig. 30), found in Mallik 2L-38 at 1140 m, is probably *T. barentsii*, occurring in a Paleocene to Late Eocene Spitsbergen flora (Manum, 1962, p. 9, 49–50, Pl. XII, fig. 24–27; Manum and Throndsen, 1986). McIntyre (1989) found *Trudopollis* species (*Trudopollis* sp., *T. barentsii*, *T. rotundus*) in Late Paleocene assemblages from Somerset Island, and in the Iceberg Bay Formation, Axel Heiberg Island.

## *A probable unconformity and/or disconformity at 1000 m*

The 1000 m horizon has sedimentological and palynological indications of a sedimentary hiatus or some other change in the regional geology or environment. Collett et al. (1999b, Fig. 1) noted the occurrence of dolomite between 1004 m and 1005 m, underlain by a coal bed between 1006 m and 1008 m. From a palynological perspective, the virtually continuous occurrence of recycled palynomorphs begins at 1010 m, starting at about 1% of all palynomorphs (Fig. 3, 6, 7) and rising gradually thorough the rest of the analyzed portion of the well. The only occurrence of *Pistillipollenites macgregorii* in the well is two specimens in the 1000 m cutting sample. The relative abundance of *Laevigatosporites* increases above 1000 m, and abundances of Ericales declines (Fig. 4). The curve of thermophilous angiosperms/total angiosperms indicates a temperature decline at about 1000 m, shown as part of a more gradual trend by the curve of Taxodiaceae-Cupressaceae-Taxaceae/ Pinaceae ('Pollen ratios and correlation to paleoclimatic temperature trends', below). The palynological percentage changes are not so abrupt as to suggest a long unconformity, but some diastem is suggested by the lithological and palynological evidence. The record of recycled palynomorphs suggests that this time marks the beginning of some significant regional erosional event, redepositing Cretaceous palynomorphs and possibly palynomorphs of other ages. The duration and significance of this hiatus is unknown.

## *Summary of correlations*

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

Figure 9 is a proposed correlation diagram of Mallik 2L-38 well, Adgo F-28 well, and Caribou Hills sections. The correlation to the Caribou Hills sections is problematic, except it is clear that the Mallik 2L-38 strata from total depth to

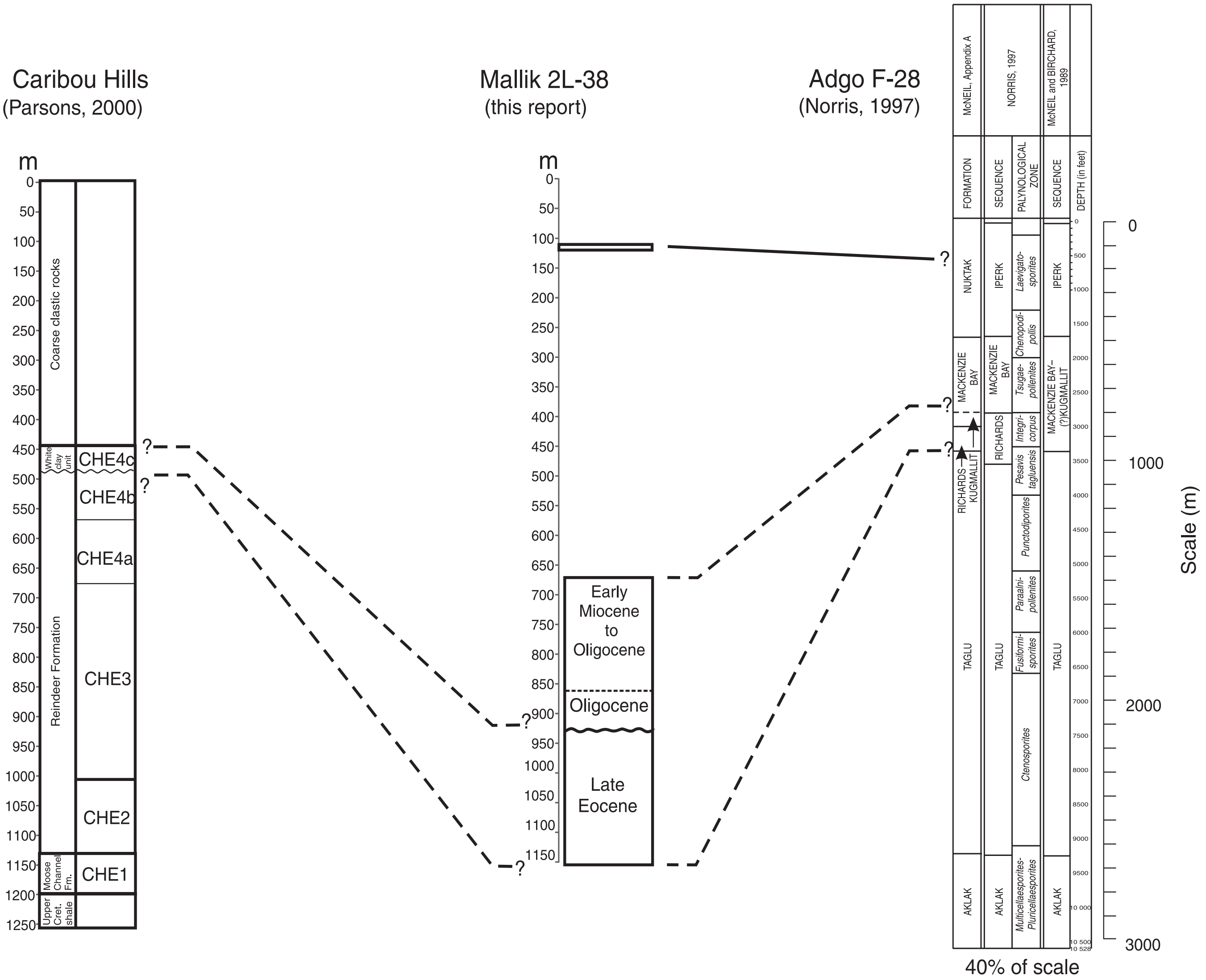


**Figure 9.** Correlation diagram, Mallik 2L-38 well, Caribou Hills sections, and Adgo F-28 well. Thickness of Caribou Hills section from Price et al. (1980). Cret. = Cretaceous

926.5 m correlate to Middle Eocene to Oligocene uppermost subzone CHE4b or subzone CHE4c or above. Mallik 2L-38 strata between 926.5 m and 1150 m correlate with strata identified in Adgo F-28 well identified as uppermost Taglu, Richards, Kugmallit, and possible basal Mackenzie Bay sequences, of Eocene and Oligocene to (?) lower Miocene age, by the old correlation or McNeil's revised stratigraphic correlation for the well (Appendix A). (The Middle Eocene uppermost Taglu Sequence is considered unlikely in the previous discussion of the Caribou Hills correlation.) Other biostratigraphic indicators argue for Eocene-Oligocene ages. *Integricorpus* sp. cf. *I. reticulatus* ranges from Late Paleocene to Oligocene (using McNeil's revised interpretation for Adgo F-28 well). *Parviprojectus* A (936.21 m) is known to occur in the Early Oligocene, although it ranges as far back as the Middle Eocene (*see* below). *Cicatricosisporites paradorogensis* (1000–1110 m) and *Boehlensipollis hohli* (1120 m) have Eocene to Oligocene ranges. *Diervilla* of McIntyre (929.23–1140 m) has been previously identified in Middle or possibly Late Eocene strata. *Trudopollis* sp. cf. *barentsii* (1140 m) is Paleocene to Late Eocene. *Boisduvalia clavatites* (943.73 m) is found in the Late Eocene Australian Creek Formation of British Columbia.

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

## *Climatic change from the Eocene to the Oligocene*

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

The climatic change from the Middle Eocene to the Oligocene was one of the most significant climatic and biological events of the Cenozoic, with evidence of cooling, drying, and greater seasonality (*see* Berggren and Prothero, 1992, and papers therein). The transition from an Eocene 'greenhouse' to an Oligocene 'icehouse' world between 40 Ma and 30 Ma was punctuated by major extinctions in tropical organisms at the end of the middle Eocene with a subsequent major global cooling event, and lesser extinctions in the early Oligocene. Minor extinctions took place in the Late Eocene and mid-Oligocene. The Eocene-Oligocene climatic transitions are thought to result from tectonic events. The Norwegian Sea–Greenland Sea opened to the North Atlantic Ocean and Australia and Antarctica separated sufficiently to allow development of circum-Antarctic circulation (Prothero, 1994), although recently it has been proposed that changes in atmospheric $CO_2$ concentration more effectively explains the cooling (DeConto and Pollard, 2003).

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

The magnitude of the late Eocene to Oligocene temperature change in Alaska has been estimated by Wolfe (1992) using the CLAMP (Climate-Leaf Analysis Multivariate Program) technique. The latest Eocene Rex Creek flora of Alaska yielded a mean annual temperature estimate of about 15°C. The Oligocene (Angoonian) assemblages, including one at Redoubt Point, Cook Inlet, yielded estimates of about 4.5°C. Wolfe (1992) estimated that the climatic deterioration occurred at about 33 Ma, about 1 Ma after the Eocene-Oligocene boundary. In addition to temperature decline, the deterioration was accompanied by a marked increase in the mean annual range of temperature.

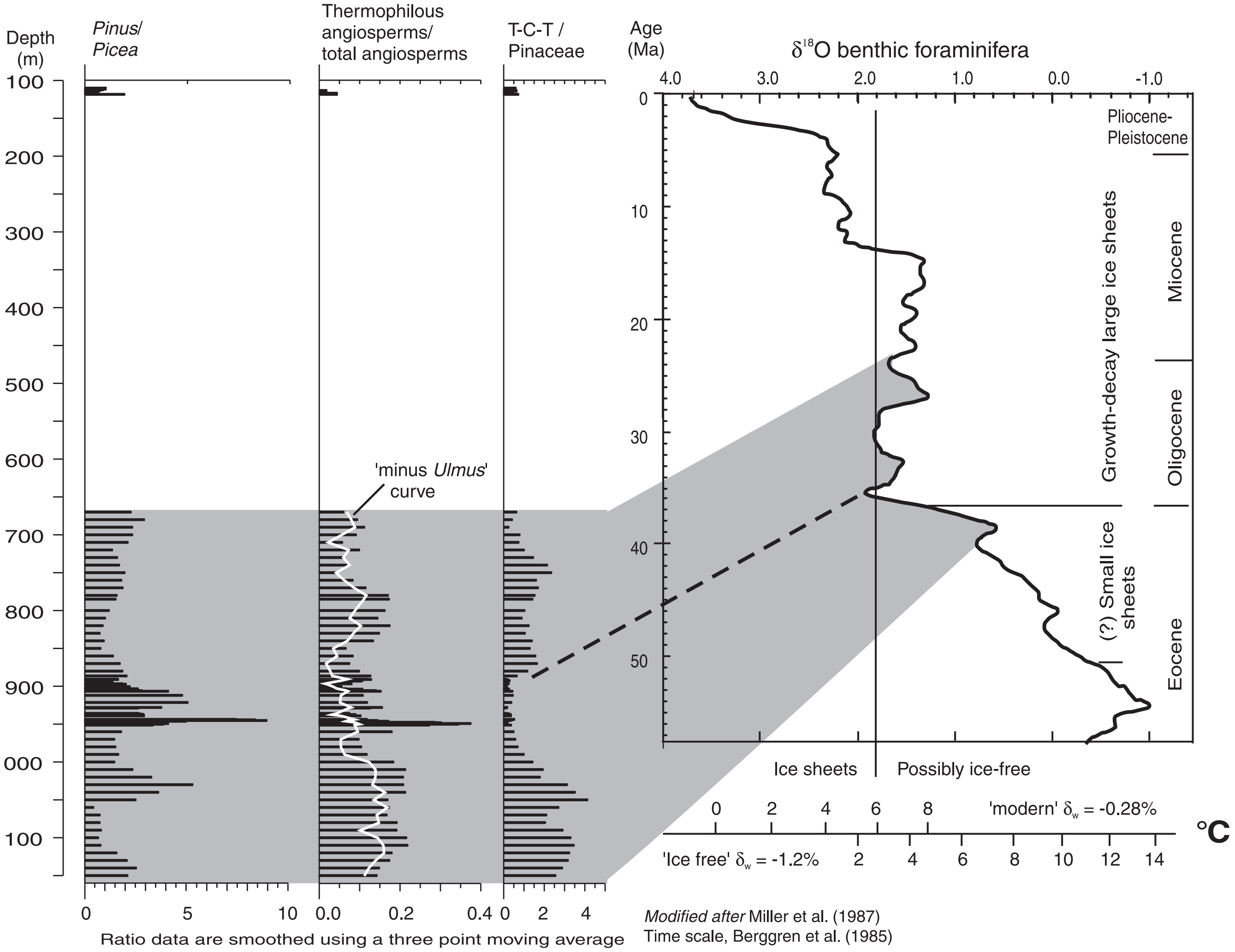
The Eocene-Oligocene vegetation change is recorded in the Burwash Basin, Yukon (Ridgway et al., 1995). Biozone 1, a Late Eocene assemblage, is angiosperm dominated with conspicuous pollen of warm-temperate taxa. Biozone 2, an Oligocene assemblage, is conifer dominated with a percentage increase of Taxodiaceae-Cupressaceae-Taxaceae pollen over biozone 1, and with a change to cool-tolerant angiosperms. Ridgway et al. (1995) concluded that the Eocene-Oligocene change was associated with increased wetness in the northwestern Cordillera.

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

From the palynology of the Nuktak C-22 well in the Beaufort-Mackenzie Basin, Norris (1982) reported that the palynoflora of the Richards Formation indicates temperate or warm-temperate climate in the middle and late Eocene, possible persisting to the early Oligocene, but a decrease in the diversity of palynofloras and some extinctions occur within prodeltaic mudstone in what was then considered to be the early Oligocene part of the Richards Formation (9600–8900 ft., 2926.1–2712.7 m). Norris (1982) reported that thermophilous taxa, including *Ulmus*, *Tilia*, *Quercus*, and *Castanea*, common in the Eocene, are not present in the lower half of the early-middle Oligocene Ivik Member, and are present higher in the late Oligocene.

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

Work on Mg/Ca ratios from benthic foraminiferal calcite (Lear et al., 2000), have corroborated the basic patterns determined by $\delta^{18}O$ measurements, and suggest an approximately 12°C deep-sea temperature drop over the last 50 Ma. The Mg/Ca ratios are at a lower chronological resolution than Miller et al.'s (1987) results, and use the time scale of Berggren et al. (1995), that places the Eocene-Oligocene boundary at 33.7 Ma. Within the Eocene decline, Lear et al.'s (2000) record showed a small temperature rise at ca. 39 Ma, followed by a monotonic decline to about 30 Ma, in the early Oligocene. Comparison of the $\delta^{18}O$ and Ca/Mg data also



*Modified after* Miller et al. (1987)
Time scale, Berggren et al. (1985)

**Figure 10.** Palynomorph ratios: thermophilous angiosperms/total angiosperms, (thermophilous angiosperms minus *Ulmus*)/total angiosperms, Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae, *Pinus/Picea*, and North Atlantic Ocean benthic foraminiferal δ $^{18}$O curve after Miller et al.'s (1987) curve. T-C-T = Taxodiaceae-Cupressaceae-Taxaceae.

suggests major ice-sheet expansion in the earliest Oligocene, although this event was not associated with a decrease in deep-sea temperatures.

Foraminiferal isotope records from the southern hemisphere provide a high-resolution record of the interval from 31 Ma to 34.9 Ma (Zachos et al., 1996), using the time scale of Cande and Kent (1992), which also places the Eocene-Oligocene boundary at 33.7 Ma. The cold interval of the earliest Oligocene, called Oi-1, spanned about 400 ka between 33.5 Ma and 33.1 Ma, and included two cold peaks, Oi-1a and Oi-1b, separated by about 150 ka. The cold episode began slowly, but the rate of temperature decline increased during the onset. The δ$^{18}$O values are interpreted to indicate the existence of a continental ice volume at least 40% of modern, and a decline in bottom-water temperatures of 3–4°C (Zachos et al., 1996). Several causal mechanisms are possible, including the tectonic opening of oceanic passages between Antarctica and South America and Australia. Milankovitch-type orbital forcing may have pushed the climate from 'greenhouse' to 'ice-house' mode, and paced the event, but a feedback mechanism of lowering pCO$_2$ is indicated by δ $^{13}$C measurements. A transfer of a large amount of carbon from the atmosphere to the ocean could have happened by increased CO$_2$ solubility in a cooler ocean, increased oceanic circulation and productivity, resulting in greater marine organic carbon burial, and by erosion of exposed continental margins (Zachos et al., 1996). Recent work emphasized the significance of the carbon cycle over tectonic factors (DeConto and Pollard, 2003). Significant glaciation was limited to a brief interval during the earliest Oligocene, the recovery was slower than the onset, but temperatures did not return to Eocene values (Zachos et al., 1996).

## *Pollen ratios and correlation to paleoclimatic temperature trends*

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

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

Within the gymnosperms, a ratio of Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae compares two major components of the pollen record. Of all the ratios, this is based on the most abundant pollen. The Taxodiaceae-Cupressaceae-Taxaceae component probably represents the pollen of the Taxodiaceae family. Deciduous *Metasequoia* and *Glyptostrobus* dominated Eocene coniferous vegetation in the North American arctic, although *Chamaecyparis* (Cupressaceae), was present (Basinger, 1991; McIver and Basinger, 1999). Taxaceae were not present or too rare to be recorded. Extant members of Taxodiaceae now grow in warm, temperate forests (Hora, 1986), and their presence in the Eocene is also likely indicative of a cold-month mean temperature greater than 0°C (Basinger et al., 1994). In particular, Taxodiaceae dominated the high-latitude wetlands during the Eocene. Megafloral records show that Pinaceae were also upland elements of high-latitude Eocene forests, and their presence argues for cool winter temperatures (Basinger, 1991; Basinger et al., 1994). The decline of Taxodiaceae and rise of Pinaceae is a significant feature of late Neogene high-latitude palynostratigraphy (White et al., 1999). Today, members of Pinaceae (*Abies, Larix, Pinus, Picea, Pseudotsuga, Tsuga*) dominate northern hemisphere mid- and high-latitude gymnosperm vegetation (Hora, 1986). Thus, geographic distributions of modern relatives suggest that this ratio may reflect a warm to cool climatic axis.

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

*Pinus* and *Picea* are the most abundant Pinaceae pollen in the Mallik 2L-38 well. In modern Pinaceae, both *Pinus* and *Picea* genera are widely distributed in the northern hemisphere, and show a wide range of climatic tolerances, but as a generalization, their modern distributions suggest that *Pinus* spp. are more tolerant of warm climates than *Picea* spp. (Hora, 1986). Thompson et al. (1999) quantified climatic tolerances of important trees and shrubs in North America. The spruces of North America grow in climates with a January temperature between −35°C and 8°C, and a July temperature between 6°C and 25°C. The pines of North America grow in climates with a January temperature between −31°C and 32°C, and a July temperature between 6°C and 32°C. Thus, spruces have slightly greater tolerance for cold January temperatures, and the same tolerance for cold July temperatures, but much less tolerance for high January and July temperatures. This may be due in part to the greater species diversity in North America of pines (50 species) over spruces (six species). Everett (1969, p. 48) noted "As a Group, the pines favour open, windswept, sunny locations and well-drained soils. They have no need of rich earth....." Everett (1969, p. 45) noted of Asiatic spruces that "...they are found almost everywhere in the colder, moist, northern and mountainous areas." In North America and Central America, *Picea* is restricted to northern and temperate regions (Thompson et al., 1999). *Pinus* occupies most of the geographic range occupied by *Picea*, except for the northern extensions of *Picea* in Yukon-Alaska and Quebec-Labrador. Unlike *Picea*, *Pinus* occupies the central and southern region of eastern United States, California, and extends much further south in the Cordillera to Honduras. Although the cold-tolerant pines *P. contorta* and *P. banksiana* currently grow at high latitudes in North America, during the late Tertiary pine diversity was much greater at high latitudes (Matthews and Ovenden, 1990). In summary, the ratio of *Pinus* spp. to *Picea* spp. should at least partially reflect a warm-dry (*Pinus* spp.) to cool-moist (*Picea* spp.) climatic gradient.

Patterns of these four ratios in the Mallik 2L-38 well (Fig. 10) from 110 m to118 m and 670 m to 1150 m confirm the general climate-driven interpretation proposed here. As expected, the Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae ratio shows that the Taxodiaceae-Cupressaceae-Taxaceae category dominates in the Paleogene, and declines through to the late Neogene. Thus, the broad-scale patterns of ratios fit known biostratigraphic trends and parallel the overall climatic cooling tendencies of the late Paleogene and Neogene. The temperate angiosperms/total angiosperms ratio shows that angiosperm taxa are much rarer in the late Neogene than in the Paleogene (the ratio 'minus *Ulmus*' could not be calculated in the late Neogene core increment). *Pinus/Picea* ratios are relatively low in the cool late Neogene (110–118 m core increment) as compared to the warmer Paleogene, although there are intervals in the Paleogene with ratios similar to the Neogene. This ratio often shows patterns different than the others, and appears to reflect factors not influencing other ratios. The features of the four ratios are compared in the following discussion.

Below the cored interval, the stratigraphic patterns for the ratios thermophilous angiosperm/total angiosperms, the inset 'minus *Ulmus*' ratio, and the Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae are remarkably similar. The earliest peak in these ratios occurs at about 1100 m; however, this is coincident with low values of the *Pinus/Picea* ratio, which had an earlier, minor peak at 1140 m. Peaks in all four ratios occur between 1050 m and 1010 m. Thermophilous angiosperms/total angiosperms, the inset 'minus *Ulmus*' ratio, and the *Pinus/Picea* ratio show sharp declines near 1000 m.

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

Within the remaining cored interval, the thermophilous angiosperms/total angiosperms ratio is variable, but values remain well below peak values. Both the main curve and the inset 'minus *Ulmus*' ratio show the same high-frequency patterns of variation. The Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae ratio has the lowest values within the core and a run of low values occur between 935.78–928.01 m. Coincidentally, recycled palynomorphs have a single peak at 937.36 m (Fig. 3), possibly representing a short episode of increased erosion. These low Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae values in the cored interval are the culmination of a trend that began at 1050 m. The *Pinus/Picea* ratio has generally higher values than average in the cored interval. As noted, this appears to also have some relationship with *Ulmus*-type pollen. Within the cored interval, all ratios independently have low values near 936 m and 900 m, reaffirming short-term climatic cyclicity within broader tends.

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

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

In contrast to the pattern below 950 m, both thermophilous angiosperms/total angiosperms and Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae ratio show out-of-phase fluctuations between 880 m and 670 m. Significant vegetation change took place across the Eocene-Oligocene boundary (*see* 'Climatic change from the Eocene to the Oligocene', above), and change in patterns between the ratios may hint at reorganization of vegetation, but the actual explanation is elusive. If this 890–670 m interval is Oligocene (below), the dramatic increase in mean annual range of temperature (above) may have changed the way in which the vegetation responded to climatic warmth.

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

Figure 10 proposes a correlation between pollen ratios and the North Atlantic Ocean $\delta^{18}O$ record from benthic foraminifera (modified after Miller et al. (1987)). The time scale for the isotopic curves is based on Berggren et al. (1985). Biostratigraphic considerations (*see* 'Summary of correlations' above) generally constrain the correlation of the 1150 m to 670 m interval of Mallik 2L-38 well to Late Eocene–Oligocene interval of the isotopic curve. Considering the major features of the ratios, the Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae best mimics the isotopic curve. In the Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae ratio, the long decline from the peak at 1150 m to the low values at 890 m, just below the top of the core, and the subsequent sharp rise in values, seems to mirror the Late Eocene–Oligocene $\delta^{18}O$ curve rise to its highest value (lowest temperature) in the early Oligocene. This point appears to provide the most certain correlation between these two curves. The bimodal peaks above the cored interval compare well with the isotopic curve in the Oligocene.

The correlation with the thermophilous angiosperm/total angiosperm ratio is less distinct, (but it is based on a much smaller number of palynomorphs) and it is different from the Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae ratio. The point of correlation between the thermophilous angiosperm/total angiosperm, including the 'minus *Ulmus*' inset curve, and the early Oligocene $\delta^{18}O$ peak seems most likely to be at 870 m. The correlation to the Oligocene portion of the $\delta^{18}O$ record is somewhat offset from the Taxodiaceae-Cupressaceae-Taxaceae/Pinaceae record.

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

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

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

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

## Reconsideration of age determinations

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

### *Age constraints on* Haplophragmoides richardsensis

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

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

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

*Wetzeliella* is thus a critical taxon for Paleogene age determinations. Williams et al. (1998) gave *W. articulata* Eisenack 1938 as the taxonomic senior synonym for *W. hampdenesis* Wilson 1967. General reviews give relatively long stratigraphic ranges for the taxon. For *W. articulata*, Powell's (1992) review gave an age of mid-Early Eocene to early Late Eocene, with a range extending to the early Early Oligocene. Williams et al. (1993) used the term *Wetzeliella articulata* 'complex' and give an early Early Eocene to early Early Oligocene age. In high-latitude North Atlantic Ocean sites that appear to be most relevant to the Arctic Ocean biostratigraphy, the age range is more restricted. In the Labrador Sea, Head and Norris (1989) found *W. articulata*, in calcareous nannofossil zones NP12, NP13, and in a calcareous nannofossil barren interval, but not in calcareous nannofossil Zone NP15, or above. This range corresponds to a stratigraphic range in the Early Eocene and possibly early Middle Eocene. Likewise, in the Norwegian Sea, *W. articulata* is abundant in the (?)Early Eocene, and is rare in the early Middle Eocene, but does not occur later (Manum et al., 1989). Thus, it appears that the Early to early Middle Eocene age for *W. articulata* is appropriate for the Arctic Ocean. (The possibility, raised by Downie et al. (1971), that the *Wetzeliella* assemblage responds to hyposalinity, is an additional consideration, but does not necessarily limit its value as a regional biostratigraphic tool.)

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

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

In Mallik L-38 well, Dixon and Peach (1988) and McNeil and Birchard (1989) noted the Richards Sequence top at 1934.0 m (6345 ft.) and indicated the presence of *Jadammina statuminus* at 2300.6 m (7548 ft.), which identifies the *Haplophragmoides richardsensis* Zone. *J. statuminis* is diagnostic of inner shelf biofacies, whereas *H. richardsensis* is characteristic of an outer shelf or deeper environment (McNeil et al., 1990). Thus, the foraminifera *J. statuminis* in the Richards Sequence indicate a shallow-marine environment in the lower Mallik L-38 well. McNeil et al. (1990) showed that diagnostic foraminifera may be recovered in only part, generally the central part, of the sequence for which they provide chronological constraints. No sequence was identified underlying the Richards Sequence to total depth.

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

## *Reconciliation of the palynomorph and foraminiferal age interpretations*

The information presented above allows the rationalization of the age interpretations of McNeil (1999) and White (1999). The first question is that of recycled foraminifera versus contemporaneous palynomorphs. Above the top of the Richards Sequence in the Mallik L-38 well, the sediment becomes a coal-bearing, largely fluvial to deltaic succession with some marine influence. In its upper strata, this delta was lithologically similar to the Kugmallit Formation delta, based on McNeil's (1999) lithological analyses of Mallik 2L-38 well. Although the fluvial-deltaic environment was unsuitable for foraminifera, it would have hosted plants. White's (1999) explanation for the discrepancy between McNeil's (1999) record of recycled forams and White's proposal that the palynomorphs were dominantly contemporaneous was this: pollen and spores from plants living in the ponds, bogs, interfluves, and adjacent uplands were deposited contemporaneously with the sediment in a fluvial-deltaic environment, but the sparse foraminifera in the sediment resulted largely from regional erosion. Hence, a dominantly recycled foraminiferal record occurs with a dominantly contemporaneous palynomorph record. Although the reworked foraminifers could not be identified to species level, a Cretaceous source is probable (McNeil, 1999), likewise a major source of recycled palynomorphs. No foraminifera diagnostic of earlier regional Paleogene successions were identified.

Deposition in the Mallik study area took place on a subsiding fault block (Brent et al., 2005). The long span of time encompassed by the Richards Sequence and Richards foraminiferal zones, 9 Ma or more, could accommodate deposition of at least 1607 m of late Middle and Late Eocene sediment (from 2533.5 m in Mallik L-38 well to 926.5 m in Mallik 2L-38 well) and some 1374 m of fluvial-deltaic-littoral sediment between the *J. statuminis* foraminiferal top in Mallik L-38 well and *Integricorpus* sp. cf. *I. reticulatus* in Mallik 2L-38 well. Similar fossils were deposited in strata offshore at Nuktak C-22 well, 27 km north, and Adgo F-28 well, 47 km west of Mallik L-38 well, in a more compressed sequence.

The Kugmallit Sequence unconformably overlies the Richards Sequence in the Ivik well to the north of the Mallik well study area (Dixon et al., 1992), and this unconformable relationship is interpreted to exist throughout the Beaufort-Mackenzie Basin. The interpretation rests on recognition of a regional unconformity in seismic interpretation, but the unconformity is not evident in the lithological logs of the Mallik L-38 well (Austin and Cumming Exploration Consultants, unpub. report, 1975). The Mallik 2L-38 well penetrates less than half of the depth of the Mallik L-38 well so the palynostratigraphy does not represent the full section, but, by the arguments presented above, the interval identified in Mallik 2L-38 well as lithologically typical of the Kugmallit Sequence, is Late Eocene, arguing that it is contemporaneous with the Richards Sequence, within the limits of the biostratigraphic resolution; 'penecontemporaneous' may be more correct. This is consistent with previous writing regarding the eponymous Kugmallit Formation. Dietrich et al. (1985, p. 621–622) said: "In the Ivik area, some of the lower, coarsening-upward cycles of the Kugmallit Formation (Ivik Member of Young and McNeil, 1982) are interpreted to be part of the uppermost beds of the Richards Sequence" and Dietrich et al. (1985) indicated a possible Late Eocene to Early Oligocene age for the oldest part of the Kugmallit Sequence. Dixon et al. (1992) also indicated that some of the lower sandstone strata assigned to the Kugmallit Formation by Young and McNeil (1984) is part of the Richards Sequence. From the perspective of this study of Mallik wells, there is merit to an interfingered, partial facies equivalence relationship of the Richards and Kugmallit formations, as attributed to Young and McNeil (1984) by Dixon et al. (1992), and as shown for the Mackenzie Delta by McNeil (1997).

These results point out that a simple short-hand equivalence of sequence and age may be difficult to apply throughout the Beaufort-Mackenzie Basin. As it is a tectonically active margin, it is difficult to explain all strata using a sequence stratigraphic model. The close association of the Kugmallit Formation with the Kugmallit Sequence illustrates the nomenclatural confusion to which Dixon et al. (1992, p. 31) alluded, in spite of the general utility of the system.

### *Correlation to the Caribou Hills sections and Adgo F-28 well*

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

Subzone CHE4c is (?) Late Eocene–Oligocene (Parsons, 2000); however, this could imply several occurrences of the important indicator palynomorph *Pistillipollenites macgregorii* in the Oligocene. In the absence of conclusive evidence of an Oligocene age, it may be best to consider subzone CHE4c as Late Eocene. Latitude may be an important consideration in the stratigraphic range of *P. macgregorii* (*see* below).

An attempted graphic correlation between Mallik 2L-38 and Adgo F-28 wells yields ambiguous results.

## Relationship to regional tectonics

On Richards Island, seismic interpretation by Brent et al. (2005) has delineated major structural features along a 12 km, southeast to northwest transect across the Taglu fault zone (Fig. 1). This transect is through four Mallik wells, and the offset on a major listric fault is suggested by the depths (below kelly bushing) to the top of McNeil's (1997)

*Haplophragmoides richardsensis* foraminiferal zone which are, from southeast to northwest: Mallik A-06, 1454.3 m (4770 ft.); Mallik J-37, 1591.5 m (5520 ft.); Mallik L-38, 2301 m (7548 ft.); and Mallik P-59, 2360 m (7740 ft.).

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

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

# CONCLUSIONS

## Recycling, ages, and tectonics

This bulletin argues that the palynostratigraphy of the Mallik 2L-38 well represents a primary biostratigraphic signal. It proposes the coherence of distributions as a standard to evaluate recycling in the biostratigraphic record. It is difficult to reconcile long-term relative abundance trends, evident in the numerically dominant taxa, and dismiss the rare indicators as recycled, especially as many rare taxa show statistically significant clustering. This standard is not a panacea, however; indeed, a strongly patterned, but explainable trend can be recognized in the whole curve of total recycled palynomorphs. Thus, these considerations assess the 'balance of evidence' regarding recycling, and do not produce a definitive answer for any particular taxon.

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

If one accepts the argument that most palynomorphs are in place, the age determinations that they indicate are: 110–118 m, Late Pliocene–Pleistocene; 118–670 m, unsampled and of known age; 670–860 m, (?) early Miocene to (?)Oligocene; 860–926.5 m, Oligocene; and 926.5–1150 m, Late Eocene.

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

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

## Proposed revisions of ranges of palynological indicators

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

*Pistillipollenites macgregorii* has been considered to be a Late Paleocene to Early to Middle Eocene indicator since Rouse (1977) published his findings. *P. macgregorii* occurs in Mallik 2L-38 well at 1000 m (*see* Pl. 4, fig. 15, 16, this study), in Late Eocene strata, and in the Caribou Hills sections in the Late Eocene strata, if one accepts the arguments presented above. While it is tempting to dismiss its occurrence in subzone CHE4c as due to recycling, other distinctive taxa such a *Ctenosporites wolfei*, *Pesavis tagluensis*, and *Striadiporites sanctabarbarae* are long ranging in the Caribou Hills sections, but do not occur above subzone CHE4b (Parsons, 2000, p. 473). Moreover, *Pistillipollenites macgregorii* was recorded once in early Oligocene strata by Marincovich and Wiggins (1990) at Unga Island, Alaska. Thus, a biostratigraphic range extension for *P. macgregorii* into the Late Eocene, and even into the early Oligocene at lower latitude, must be entertained. *P. macgregorii*'s Eocene range suggests that it may have had a preference for a warm climate or a climate without temperature extremes. It is thus conceivable that it survived longer at Unga Island, currently at 55°N, near the moderating influence of the Pacific Ocean, than in northern Yukon, currently at 69°N, under a stronger continental influence.

In the arctic, *Paraalnipollenites alterniporus* was first known to range though the Paleocene (Rouse, 1977), but more recent work shows that its stratigraphic range extends upward, although its occurrence may not be common. Long and Sweet (1994) found it in a late Eocene assemblage in the Rock River coal basin, Yukon. In Parsons' (2000) analysis of the Caribou Hills sections, subzone CHE4c, of probably Late Eocene age (above) has one occurrence of *P. alterniporus*, but it is much more common in Early to Middle Eocene zone CHE3 and subzones CHE4a, CHE4b (Parsons, 2000); by the correlation proposed above, upper subzone CHE4b may extend to the Late Eocene. The range of *P. alterniporus* has been reported by Ioannides and McIntyre (1980) to extend into the Oligocene, but the reassignment of the Chadronian to the Late Eocene (Prothero and Swisher, 1992) causes the reassignment of the Australia Creek Formation assemblage (Piel, 1971; Rouse and Mathews, 1979), to which Ioannides and McIntyre (1980) correlated, to the Late Eocene (Long and Sweet, 1994). Thus the youngest firm record to date of *P. alterniporus* is Late Eocene, fitting with its occurrence in Mallik 2L-38 well up to 947.61 m (Pl. 3, fig. 17); however, if the ages for Mallik 2L-38 well strata have been interpreted correctly, a single specimen of *P. alterniporus* at 890.71 m is in the earliest Oligocene.

*Psilastephanocolpites* cf. *marginatus* Gonzales Guzman 1967 of Norris (1997, Pl. 6, fig. 2, 3, 5) is the same as Tetracolporate B of Piel (1971, Pl. XII, fig. 93, 94). This taxon is found in Mallik 2L-38 well strata at 1060 m and 1140 m (Pl. 4, fig. 20, 21, 23). White (1999) used this specimen as evidence of a Middle Eocene age, following Norris (1997), but the close comparison with Piel's (1971) Tricolporate B specimens indicates that the stratigraphic range of this taxon extends upward to the Late Eocene (Long and Sweet, 1994).

*Diervilla* of McIntyre (1991, Pl. 4, fig. 1, 2) was originally recorded in the fossil forest of the Buchanan Lake Formation, northeast Axel Heiberg Island, in strata reported to be Middle Eocene, or possibly Late Eocene (McIntyre, 1991). *Diervilla* of McIntyre (1991) is found in Mallik 2L-38 well strata between 1140 m and 945.21 m and in a supplementary coal sample from 929.23 m, in strata interpreted to be Late Eocene (Pl. 3, fig. 11, 18). As the upper record comes from a coal sample, in which recycling is very unlikely, this implies a range extension for this taxon into the Late Eocene.

*Jussiaea* (*see* Piel, 1971, Pl. XVII, fig. 152, 153) was recorded in the Mallik 2L-38 well as *Jussiaea (Ludwigia)* sp., occurring between 928.01 m to 785 m (Pl. 4, fig. 4). It was originally found in the Late Eocene Australian Creek Formation (Piel, 1971; Long and Sweet, 1994). It is not recorded in the Caribou Hills sections (Parsons, 2000) or the Adgo F-28 well (Norris, 1997). It occurs in the Burwash Basin in Biozone 1 of the Late Eocene (Ridgway et al., 1995). The range in Mallik 2L-38 well suggests a range from Late Eocene into the Oligocene.

*Boisduvalia clavatites* Piel 1971 is very rare in subzone CHE4b (possibly in a slump block, above) and subzone CHE4c (Parsons, 2000) of Middle and Late Eocene age (above). *Boisduvalia clavatites* is found in the Late Eocene Australian Creek Formation of British Columbia (Piel, 1971; Long and Sweet, 1994) and in Late Eocene Biozone 1 of the Amphitheatre Formation, Yukon (Ridgway et al., 1995). *B. clavatites* does not occur in the Nuktak C-22 well or the Adgo F-28 well (Norris, 1986, 1997). In Mallik 2L-38 well it is found at 943.73 m (Pl. 3, fig. 10), also in Late Eocene rocks. Thus, its range is apparently Middle Eocene (probably late Middle) to Late Eocene.

In Mallik 2L-38 well, *Diervilla echinata* is found at 740 m in probable Oligocene rocks (Pl. 4, fig. 3). *Diervilla echinata* has been recorded in Early Eocene to early Middle Eocene beds in the Gang Ranch–Big Bar area of central British Columbia (Mathews and Rouse, 1984) and in Late Eocene Australian Creek Formation (Piel, 1971; Long and Sweet, 1994). Ioannides and McIntyre (1980) recorded it in Caribou Hills sections in strata that are included in Parsons' Late Eocene subzone CHE4c (above). *Diervilla/Weigela* has been recorded in the Yukon–interior Alaska area in beds belonging to the Cyperaceae Subzone, estimated as young as 6.15 Ma (White et al., 1999). *Diervilla echinata* and *Diervilla/Weigela* are probably equivalent, representing a modern taxon ranging back to the Early to Middle Eocene.

*Lonicerapollis gallwitzii* occurs in Mallik 2L-28 well sporadically from 1150 m to 1110 m with records of possibly related Caprifoliaceae taxa at 903.01 m and 897.36 m (Pl. 4, fig. 7a, b). In the Adgo F-28 well, the last occurrence datum *of L. gallwitzii* occurs at 2300–2400 ft. (701.0–731.5 m) in the Mackenzie Bay Formation, with its base at 2800–2900 ft. (853.44–883.92) in the upper Kugmallit Formation (Norris, 1997; Appendix A). It was not observed in the Caribou Hills sections (Parsons, 2000). The age range suggested by these occurrences is Late Eocene to Late Oligocene–Early Miocene.

*Parviprojectus* A of Rouse (1977) (Pl. 5, fig. 20a, b) was originally defined as an Oligocene indictor by Rouse (1977; Rouse and Mathews, 1979) as a result of an Australian Creek occurrence in central British Columbia, a record which would now be considered to be Late Eocene (Piel, 1971; Long and Sweet, 1994). *Parviprojectus* A occurs in Early Oligocene rocks in the Amphitheatre Formation, Burwash Basin, Yukon (Ridgway et al., 1995) and at Unga Island, Alaska (Marincovitch and Wiggins, 1990). The Oligocene (now Late Eocene) age interpretation was also used by Staplin (1976), where the top of *Parviprojectus* A (as PJ-1) was also considered as the Paleogene-Neogene boundary in Imperial Oil Enterprises Taglu C-42 and G-33 wells. Staplin (1976) indicated that the species has been found in wells off the Grand Banks, in association with *Wetzeliella articulata* and other Early to Middle Eocene fossils, and *Parviprojectus* A (as *Integricorpus* sp. A) occurs in the Richards Sequence in Nuktak C-22 well (Norris, 1986; Dixon, 1990); however, Parsons (2000) did not see *Parviprojectus* A of Rouse (1977) in her intensive study of the Richards and Taglu sequences in the Caribou Hills sections, indicating that the species is rare, and consequently, its stratigraphic range will be difficult to precisely define. If all of these occurrences are validly dated, the range of *Parviprojectus* A of Rouse (1977) would appear to be from Middle Eocene to Early Oligocene. Its occurrence may depend on climatic or environmental tolerances, as yet unknown.

*Integricorpus* sp. cf. *I. reticulatus* (Pl. 5, fig. 18a, b, 19a, b) occurs from Late Paleocene or Early Eocene lower zone CHE3 in the Caribou Hills sections to the Oligocene Kugmallit Sequence in Adgo F-28 well (Norris, 1997; McNeil, Appendix A).

*Striatocorpus sweetii* sp. nov. (Pl. 5, fig. 21, 22, 23) occurs in Mallik 2L-38 well at 990 m, 1040 m, 1130 m, and 1140 m, below *Integricorpus* sp. cf. *I. reticulatus*. These rocks are interpreted to be Late Eocene. This triprojectate species is described in Appendix B.

## Implications for gas-hydrate accumulation

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

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

# SUMMARY

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

- On the basis of finding coherent patterns in concentration, in relative abundance of common taxa and in clustering of rare taxa, it is argued that palynomorph distributions in Mallik 2L-38 well cannot be readily explained by recycling, and that the palynological record yields a primary biostratigraphic signal. The regional environment of deposition would have supported abundant vegetation that would have contributed a prodigious amount of pollen and spores to the sedimentary record. If the numerically dominant taxa are largely in place, it seems unreasonable to dismiss the indicator taxa as being largely recycled.
- Biostratigraphy by quantitative analysis of the Mallik 2L-28 well provide the basic data, but an attempt has been made to augment and refine the age interpretation by correlation to information outside the basin, specifically by comparing the experimental paleoclimatic signal extracted from the Mallik 2L-38 data to the North Atlantic Ocean $\delta^{18}$O records. This comparison argues that the Early Oligocene temperature minimum is recorded in sediment adjacent to 897 m, which is the top of the gas-hydrate-hosting interval. From this reference position, the probable position of the Eocene-Oligocene boundary is identified as the disconformity at 926.5 m in the Mallik 2L-38 well.
- The palynomorph ratios used to extract the paleoclimatic data from Mallik 2L-38 well have not been used in other studies, so this represents an initial attempt to provide a tool to correlate to an independent paleoclimatic signal. Obviously, the behaviour of those ratios over a much longer Cenozoic section needs to be accumulated and assessed to improve the reliability of the interpretations.
- A discussion of the taxonomy of Paleogene triprojectate fossils relevant to age determination in Mallik 2L-38 well has separated *Integricorpus* sp. cf. *I. reticulatus* from *Parviprojectus* A. *Striatocorpus sweetii*, a new Paleogene species, is named. By current interpretation, it occurred in the Late Eocene. The Paleogene triprojectate lineage requires further study.
- The discrepancy in age determination between McNeil (1999) and White (1999) is explained as a result of the termination of the foraminiferal record in a shallow-marine environment, which became a fluvial-deltaic environment with some marine influence. Although the *Haplophragmoides richardsensis* zone was identified

in the lower, marine interval, the chronological and environmental record is then continued by continental fossils. In the area of Mallik L-38 and 2L-38 wells, about 1 km of sediment was deposited during the Late Eocene, above the apparent top of the Richards Sequence. The *Haplophragmoides richardsensis* foraminiferal zone spans 9 Ma or more, allowing adequate time for such deposition.

- Correlation to the Caribou Hills sections is problematic, although it is clear that the Lower to Middle Eocene interval, below uppermost palynological subzone CHE4b, is not represented in the Mallik 2L-38 well. Correlation based on *Integricorpus* is most straightforward, but is not entirely satisfactory considering the ranges of other taxa and the age implications; however, the *Integricorpus* correlation, and the time constraints of the *Haplophragmoides richardsensis* Zone in Mallik L-38 well, suggests the possibility that uppermost subzone CHE4b is Late Eocene, rather than Middle Eocene. Of the age alternatives proposed by Parsons (2000) for subzone CHE4c, the "Late Eocene" age is preferred over the "?Oligocene" age. This age does not then imply a significant Oligocene occurrence of *Pistillipollenites macgregorii*, and a rare occurrence of *Paraalnipollenites alterniporus*. Nonetheless, an occurrence of *Pistillipollenites macgregorii* in Oligocene rocks at Unga Island, Alaska is to be noted, but is likely a late range extension in a more southerly and climatically moderated environment.
- The biostratigraphic and paleoclimatic analyses presented above suggest that the Eocene-Oligocene boundary is near the unconformity at 926.5 m in Mallik 2L-38 well, and occurs within sediment identified lithologically as part of the Kugmallit Sequence, or as just above the Kugmallit–Mackenzie Bay sequence boundary. It has been accepted that some Kugmallit Formation sediment may be Late Eocene.
- The 897 m top of the main accumulation of gas hydrate appears to nearly coincide with a geologically defined boundary, shown by independent aspect of the palynological evidence, including changes in palynomorph concentration, percentages of common taxa, and in ratios expected to track paleoclimate. Although the climatic evidence is independent of the age interpretation, this interval is interpreted to be the Early Oligocene cool event. This boundary is not detected by conventional geophysical logging tools, the records of which are dominated by the postdepositional accumulation of gas hydrate.
- In Mallik 2L-38 well there is likely a sedimentary diastem near 1000 m, and evidence from recycled palynomorphs suggests that this time in the Late Eocene marks the beginning of some regional unroofing of Cretaceous rocks.
- White's (1999) age determinations for Mallik 2L-38 well are significantly revised here, but uncertainties remain in regards to the age of the sediment from 1150 m to 880 m (*see* above), and particularly with regard to the age range of the sediment between 880 m and 670 m. This latter problem is due to the absence of useful indicator species and because of the long interval without fossil recovery above 670 m, which deprives the interpretation of the constraints from overlying biostratigraphic events. Stratigraphic range extensions may explain the late occurrences of taxa associated with the Taglu Sequence in Adgo F-28 well, but recycling cannot be excluded.

The age determinations argued for herein are:

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

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

- The site of Mallik L-38 well, outboard of a major normal fault in the Taglu fault zone, was probably an area of active subsidence and deposition during the Eocene. This tectonic evidence is consistent with the biostratigraphic evidence of a much greater thickness of Late Eocene deposition than previously identified.

## QUESTIONS FOR FUTURE RESEARCH

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

- Produce a formal classification of Paleogene triprojectate species and accumulate further evidence regarding their biostratigraphic ranges, including *Striatocorpus sweetii* sp. nov.
- Accumulate more evidence of the biostratigraphic ranges and the influence of environmental tolerances on the distributions of important palynomorph indicator taxa, including the *Wetzeliella* complex, *Pistillipollenites macgregorii*, *Integricorpus* sp. cf. *I. reticulatus* (Mtchedlishvili) Stanley 1970 of Parsons (2000), and *Parviprojectus* A of Rouse (1977).
- Extend the use of ratios over a longer chronostratigraphic range, with investigation of new ratios, in an attempt to correlate within and outside the Beaufort-Mackenzie Basin by data independent of sporadic occurrences of rare taxa.

- Collect and curate quantitative biostratigraphic data from the Beaufort-Mackenzie Basin so that hypotheses can be developed and tested using accumulated sets of data. The data should include micropaleontological as well as palynological data, so the relationships between these fossil groups can be explored. Such data sets are probably the only way of approaching the question of the environmental tolerances of various palynomorphs.
- Re-examine an important underpinning of Late Eocene–Oligocene palynostratigraphy by re-studying Australian Creek sections, from which titanothere teeth provide a critical correlation between the palynological assemblage of western and northern Canada and Alaska and the North American land mammal chronology.

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# Appendix A

## Revised foraminiferal last occurrence data for Adgo F-28

D.H. McNeil

## NEW DATA FOR ADGO F-28 WELL FOLLOWING EXAMINATION OF MICROSLIDES ACQUIRED FROM ESSO RESOURCES CANADA LIMITED AND AMOCO CANADA PETROLEUM COMPANY

1470’ (448.06 m): *Asterigerina staeschei*, poor recovery, possibly reworked or contaminated; Amoco Canada Petroleum Company slides.

1680’ (512.06 m): *Asterigerina magnus* (Oligocene), good recovery from 1680’ (512.06 m) to 1860’ (566.93 m), specimens iron-stained, possibly reworked or contaminated; Amoco Canada Petroleum Company slides.

1710’ (521.21 m): *A sterigerina staeschei* (Middle Miocene to Oligocene), very good recovery; Esso Resources Canada Limited slides.

1950’ (594.36 m): *Turrilina alsatica* (Oligocene), very good recovery; Esso Resources Canada Limited slides.

2970’ (905.26 m): *Valvulineria dixoni* (Early Oligocene, one specimen), very good Oligocene assemblage; Esso Resources Canada Limited slides.

(3083’ (939.70 m): casing)

3085’ (940.31 m): last downhole occurrence of Oligocene assemblages; Esso Resources Canada Limited slide.

3270’ (996.70 m): fish fragments and algal cysts typical of Richards-Taglu sequence transition.

3450’ (1051.56 m): abundant coal.

## STRATIGRAPHY

**Nuktak Formation**: base appears to be at 1700’ (518.16 m). A sandy zone from about 1500’ (457.20 m) to 1700’ (578.16 m) contains Miocene and Oligocene foraminifera, but the assemblages are poorly developed and are possibly reworked in a regressive or transgressive sand unit.

**Mackenzie Bay Formation**: top appears to be at 1700’ (518.16 m). Base is difficult to recognize on the logs. Tentative pick is at 2800’ (853.44 m).

**Kugmallit Formation**: upper contact is difficult to recognize on the logs, but tentatively picked at 2800’ (853.44 m). *Valvulineria dixoni* at 2970’ (905.26 m) indicates probable lower Kugmallit Formation. The lower contact occurs at approximately 3000’ (914.40 m).

**Richards Formation**: top occurs at approximately 3000’ (914.40 m). Base well defined at 3360’ (1024.13 m).

**Taglu Formation**: top well defined at 3360’ (1024.13 m). *

The Richards-Taglu formation transition is well defined in the Adgo F-28 well, based on logs, palynology, and a few microfossils. The foraminiferal recovery for the Oligocene in the Adgo F-28 well is very good, but the formational contacts between the Kugmallit and Mackenzie Bay formations are only tentatively picked because the contacts are not obvious on the logs. The top of the Mackenzie Bay Formation is picked at 1700’ (518.16 m) and this is supported by the Esso Resources Canada Limited slides and the logs. The Amoco Canada Petroleum Company slides contain Oligocene foraminifera between 1680’ (512.06 m) and 1860’ (566.93 m), but this is not matched by Esso Resources Canada Limited slides and it may represent either contamination or possibly reworking (since there is a well defined sandy unit from 1500’ (457.20 m) to 1700’ (518.16 m)). In summary, the Richards Sequence is well documented in the Adgo F-28 well. The overall succession in the neighbouring Adgo J-17 well is similar to Adgo F-28 well.

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* The Taglu top has been revised downward to 1364.6 m by Dixon et al. (2009)

# Appendix B

## *Striatocorpus sweetii* sp. nov.

*Striatocorpus* (Krutzsch) Farabee, Vezey and Skarvala 1991.

*Striatocorpus sweetii* sp. nov.

*Holotype:* Pl. 5, fig. 22 a, b, C-400771, P4364–96a, 100.1 mm x 18.3 mm, Mallik 2L-38 well, depth 1130 m.

*Paratype:* Pl. 5, fig. 21, C-400755, P4364–82a, 80.1 mm x 13.1 mm, Mallik 2L-38 well, depth 990 m.

## DIAGNOSIS

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

## DESCRIPTION

### Shape

Specimen Plate 5, figure 22, the holotype of *Striatocorpus sweetii* sp. nov., and Plate 5, figure 21, are clearly presented in equatorial view and are similar in shape. The shape of the holotype is that of an isoscelese to nearly equilateral triangle, the angles being near 60°. It is strongly heteropolar, and has a much reduced minor pole; in the holotype, the outline of the third equatorial projection exaggerates the size of the minor pole. The apex is broadly rounded and the maximum equatorial breadth is about three quarters of the distance from the larger pole to the base, due to the rounding of the basal angles. The paratype specimen Plate 5, figure 21 has a similar apical angle to the holotype and is generally similar in shape, but the folding of the grain makes it impossible to discern the minor pole. Both specimens shown in Plate 5, figures 21 and 22 are somewhat concave between the polar dome and the equator.

### Size

For three measured specimens the polar and equatorial size is 18–20 µm and 22 µm, for a ratio of about 0.86.

### Apertures

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

### Ornament

The grains are ornamented by parallel striae. The striae in the holotype are exaggerated in Plate 5, figure 22b, processed with an unsharp mask filter. The striae on the projections nearest to the polar axis are oriented approximately parallel to, or tilt somewhat outward, from the polar axis. Striae increasingly distant from the polar axis tilt outward from that axis so that those on the distal equatorial projections appear to radiate from a central point.

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

## DISTRIBUTION AND AGE

*Striatocorpus sweetii* occurs in the Mallik 2L-38 well at 990 m, 1040 m, and 1130 m, below the last occurrence datum of *Integricorpus* sp., cf. *I. reticulatus*, which is at 950.11 m; cf. *S. sweetii* occurs at 1140 m. *A. sweetii* occurs in rocks that are argued to be Late Eocene.

## COMPARATIVE REMARKS

The specimen at 1140 m, Plate 5, figure 23 (C-400772, P4364–97a, 93.9 mm x 21.2 mm, Mallik 2L-38 well) is referred to *S. sweetii*, and may represent the range of variation in shape in the equatorial view. This specimen occurs 10 m below the holotype, they are both the only triprojectate grains in either sample, and are of similar size, with same striate ornament. Thus, it seems likely that they belong to the same population. Specimen shown in Plate 5, figure 23 is more rhombic with an apical angle of about 105°. The point of maximum breadth is about midway between poles, and the sides are nearly straight. Compared to the major pole, the specimen, Plate 5, figure 23's minor pole is indicated more by its smaller diameter and more abrupt discontinuity from the equatorial outline of the grain. The third equatorial projection, on the plane of the viewer's eyes, is bent sideways and flattened against the other projection, so the minor pole may be somewhat exaggerated by crushing. Even if the minor pole is somewhat exaggerated, the base of the grain is more rounded than the other specimens, and the maximum equatorial diameter is about midway between the poles. In Figure 4a in this study, it is included in the stratigraphic distribution of *S. sweetii*. This specimen appears to have a faint infra-microreticulum, visible at the limits of optical resolution, whereas in the holotype this feature is not visible, but is faintly visible in the paratype specimen (Pl. 5, fig. 21, at 990 m), also at the limits of optical resolution.

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

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

*Striatocorpus sweetii* is similar in ornament to a specimen of *Mancicorpus* sp. (Ridgway et al., 1995, Fig. 13, specimen I) from the Late Eocene, Biozone 1 in the Amphitheatre Formation, Burwash Basin, southwest Yukon, but in the *Mancicorpus* specimen the projections narrow distinctly distally and angle toward the minor pole, it does not exhibit a concave outline between the polar dome and the equator, and the polar diameter is about two thirds of the equatorial diameter. Farabee et al. (1991) noted that Nichols has found specimens of *Striatocorpus* in the Upper Eocene to Oligocene of Alaska, however, the basis on which the age was determined is not presented (*see* discussion above "Proposed revisions of ranges of palynological indicators" about the reassignment of the Australian Creek Formation to the Late Eocene). Farabee et al. (1991) indicated that most species of *Striatocorpus* are restricted to the Maastrichtian of North America.

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

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

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

# Appendix C

## List of taxa used in this study

The names below derive from modern botanical and paleobotanical names. Authorship 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. 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 the family has been put in the genus field, and 'undiff.' in the species field. For unknown palynomorphs, 'Mallik2L-38' fills the genus field, and 'unknown nn' fills the species field. This usage is informal nomenclature, but securely designates the palynomorphs so that it can be named when appropriate and modified in the database. This is preferable to using the form 'Species A'.

## ACRITARCHS

*Baltisphaeridium* spp.

*Cymatiosphaera* sp.

*Lecaniella foveata* Singh 1971

*Micrhystridium* group of Sarjeant and Stancliffe 1994

*Pterospermopsis* sp.

## PROTISTS

Algae spp.

*Botryococcus* sp.

*Ovoidites ligneolus* (Potonié) Potonié 1951

*Schizosporis reticulatus* Cookson and Dettmann 1959

*Sigmopollis carbonis* (Newman) Srivastava 1984

*Sigmopollis hispidus* Hedlund 1965

*Sigmopollis* sp.

## DINOFLAGELLATES

*Chatangiella ditissima* (McIntyre) Lentin and Williams 1976

*Cleistosphaeridium* sp.

*Deflandrea* sp.

Dinoflagellate indet.

*Habibacysta tectata* Head, Norris and Mudie 1989

*Hystrichosphaeridium* sp.

*Labyrinthodinium truncatum* Piasecki 1980

*Operculodinium centrocarpum* (Deflandre and Cookson) Wall 1967

*Operculodinium* sp.

*Spiniferites* sp.

## FUNGI

*Basidiosporites* sp.

*Brachysporisporites* sp.

*Desmidiospora* sp.

*Diporicellaesporites* sp.

*Diporisporites* sp.

*Dyadosporites* sp.

*Equisetum* sp.

*Foveodiporites* sp.

*Fractisporonites* sp.

Fungi hyphae

Fungi hyphae type A of Norris (1986)

*Hypoxylonites* sp.

*Inapertisporites pisciculatus* (Norris) Kalgutkar and Jansonius 2000

Mallik2L-38 unknown 02

Mallik2L-38 unknown 13

Mallik2L-38 unknown 26

*Monoporisporites* sp.

*Multicellaesporites* sp.

*Pluricellaesporites* sp.

*Polyadosporites* sp.

*Reduviasporonites* sp.

*Striadiporites inflexus* (Ke et Shi ex Sung et al.) Norris 1986

## BRYOPHYTES

*Sphagnum* sp.

*Stereisporites micrograndulus* sensu Norris (1986)

## FERNS AND FERN ALLIES

*Acanthotriletes varispinosus* Pocock 1962

*Anemia*-type

*Baculatisporites comaumensis* (Cookson) Potonié 1956

*Baculatisporites crassiprimarius* (Krutzsch) Norris 1986

*Baculatisporites primarius primarius* (Wolfe) Thomson and Pflug 1953

*Baculatisporites quintus* (Thompson and Pflug) Krutzsch sensu Norris (1986)

*Cibotiumspora jurienensis* (Balme) Filatoff 1975

*Cicatricosisporites augustus* Singh 1971

*Cicatricosisporites australiensis* (Cookson) Potonié 1956

*Cicatricosisporites paradorogensis* Krutzsch 1959

*Cicatricosisporites* sp.

*Concavisporites* sp.

*Cristatisporites orcadensis* Richardson 1960

*Deltoidospora* sp.

*Densosporites rarispinosus* Playford 1963

*Equisetum* sp.

*Foveosporites* sp.

*Gleicheniidites senonicus* Ross 1949

*Impardecispora apiverrucata* (Pant ex Pot.) Venkatachala, Kar and Raza 1969

*Impardecispora marylandensis* (Brenner) Srivastava 1975

*Impardecispora minor* (Pocock) Venkatachala, Kar and Raza 1969

*Laevigatosporites* sp.

*Lycopodium inundatum*

*Lycopodium selago*

*Lycopodium* sp.

*Lycopodiumsporites marginatus* Singh 1964

Mallik2L-38 unknown 01

Mallik2L-38 unknown 08

Mallik2L-38 unknown 14

Mallik2L-38 unknown 17

*Murospora* sp.

*Osmunda irregulites* Martin and Rouse 1966

*Osmunda regalis*

*Osmunda* sp.

*Osmundacidites wellmanii* Couper 1953

Polypodiaceae-Dennstaedtiaceae

*Retitriletes* sp.

*Retitriletes* sp. cf. *R. novomexicanus* (Anderson) Norris 1986

*Selaginella selaginoides*

*Trilobosporites* sp.

*Tripartites incisotrilobus* (Naumova) Kraczewska and Turnau 1974

*Verrucatosporites favus* (Potonié) Thompson and Pflug 1953

## GYMNOSPERMS

*Abies* sp.

*Cedrus* sp.

*Classopollis classoides* (Pflug) Pocock and Jansonius 1961

*Ephedra* sp.

*Equisetum* sp.

*Larix*- and/or *Pseudotsuga*-type of White and Ager (1994)

Mallik2L-38 unknown 23

*Metasequoia*-type

*Picea* sp.

*Picea* sp. (robust corpus)

*Picea* sp. (small)

Pinaceae

*Pinus* (robust corpus) of White and Ager (1994)

*Pinus koraiensis*-type of White and Ager (1994)

*Pinus* sp.

*Podocarpus*-type

*Pristinuspollenites microsaccus* (Couper) Tschudy 1973

*Pristinuspollenites pannosus* (Pierce) Tschudy 1973

*Rugubivesiculites* sp.

*Sciadopitys* sp.

Taxodiaceae-Cupressaceae-Taxaceae undiff. of White and Ager (1994)

*Tsuga canadensis*-type of White and Ager (1994)

*Tsuga heterophylla*-type of White and Ager (1994)

*Tsuga* sp.

*Vitreisporites pallidus* (Reissinger) Nilsson 1958

## ANGIOSPERMS

*Acer* sp.

*Aceripollenites tener* (Samoilovitch) Norris 1997

*Alnus* four-porate

*Alnus* five-porate

*Alnus* six-porate

*Alnus* sp.

*Alnus trina* Stanley 1965

*Annutriporites* sp. A of Norris (1986)

Apiaceae

*Aquilapollenites clarireticulatus* (Samoilovitch) Tschudy 1969

*Aquilapollenites magnus* (Mtchedlishvili) Frederiksen 1991

*Aquilapollenites quadrilobus* Rouse 1957

*Aquilapollenites* sp.

*Aquilapollenites trialatus* Rouse 1957

*Aquilapollenites unicus* (Khlonova) Khlonova 1961

*Artemisia* sp.

*Betula* ≤20 µm

*Betula* >20 µm

*Boehlensipollis hohli* Krutzsch 1962

*Boisduvalia clavatites* Piel 1971

Brassicaceae

Caprifoliaceae

*Carya* sp.

Caryophyllaceae

*Castanea*-type of White and Ager (1994)

Chenopodiineae

*Cornus* sp.

*Cornus stolonifera*-type

*Corylus*-type

Cyperaceae

*Diervilla echinata* Piel 1971

*Diervilla* of McIntyre (1991)

Droseraceae

Ericales

*Fagus* sp.

*Fraxinus* sp.

*Gothanipollis*? sp.

*Ilex*-type of White and Ager (1994)

*Integricorpus* sp., cf. *I. reticulatus* (Mtchedlishvili) Stanley 1970 of Parsons (2000)

Iridaceae-Liliaceae

*Juglans* sp.

*Jussiaeae* (*Ludwigia*) sp.

*Labrapollis* sp. Krutzsch 1968

*Liquidambar* sp.

*Lonicerapollis gallwitzii* Krutzsch 1962

*Magnolia* sp.

Mallik2L-38 unknown 03

Mallik2L-38 unknown 04

Mallik2L-38 unknown 05

Mallik2L-38 unknown 06

Mallik2L-38 unknown 09

Mallik2L-38 unknown 10

Mallik2L-38 unknown 11

Mallik2L-38 unknown 12

Mallik2L-38 unknown 15

Mallik2L-38 unknown 16

Mallik2L-38 unknown 18

Mallik2L-38 unknown 19

Mallik2L-38 unknown 21

Mallik2L-38 unknown 22

Mallik2L-38 unknown 24

Mallik2L-38 unknown 25

Mallik2L-38 unknown 27

Mallik2L-38 unknown 28

Mallik2L-38 unknown 29

Mallik2L-38 unknown 30

Mallik2L-38 unknown 31

*Momipites wyomingensis*? Nichols and Ott 1978

*Nyssa* sp.

*Ostrya-Carpinus*

*Paraalnipollenites alterniporus* (Simpson) Srivastava 1975

*Parviprojectus* A of Rouse (1977)

*Pistillipollenites macgregorii* Rouse 1962

*Planera* sp.

Poaceae

*Polyvestibulopollenites trinus* (Stanley) Norris 1986

*Psilastephanocolpites* cf. *marginatus* Gonzales Guzman of Norris (1997)

*Pterocarya* sp.

*Quercus* sp.

*Retimonocolpites excelsus* Ward 1986

*Retitricolpites* sp.

*Rhoipites* sp.

*Rhoipites* sp. cf. *R. microreticulatus* (Pflug and Thompson) Takahashi and Jux of Norris (1997)

*Ribes* sp.

Rosaceae

*Salix* sp.

Shepherdia *canadensis*

*Sparganium* sp.

*Striatocorpus sweetii* sp. nov.

*Tetracolpites* sp.

Tetrad pollen (scabrate)

*Tetraporate* sp.

*Tilia* -type of White and Ager (1994)

*Tricolpites* sp.

*Tricolpopollenites* sp.

*Tricolporopollenites* sp.

*Triporopollenites* sp.

*Trudopollis barentsii*? Manum 1962

Tubuliflorae

*Ulmus*-type of White and Ager (1994)

*Wodehouseia spinata* Stanley 1961

## INCERTA SEDIS

Mallik2L-38 unknown 07

## OTHER

*Lycopodium* spike

Recycled palynomorphs

Undeterminable spp.

# Appendix D

## Palynological analysis records for Mallik 2L-38

A list of raw results of the palynological analysis of the Mallik 2L-38 well is found on CD-ROM. 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 of each taxon.

The comments field below a taxon may give the microscope slide letter and stage Co-ordinates (in millimetres) for the specimen and a digital image number (nnnn.tif) in the author's digital photographic records. 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 slide label to the left and facing the observer) by subtracting 61.9 mm from the 'X' Co-ordinate and 0.6 mm from the 'Y' Co-ordinate.

The listed percentages are created by Stratabugs version 1.7 (http: www.stratadata.co.uk/), and are based on the all of the fossils in the sample. They do not correspond with the percentages in this manuscript, which are based on various sums and subsums (Table 1).

**Note:** The symbols u (should be µm) and A'm (should be µm) are not consistently and correctly represented in this Appendix due to technical difficulties arising from converting the database file.

# Plate captions

Note: Palynomorph measurements are for the polar and equatorial axes or for the single longest visible dimension. Some palynomorph specimens may not match the size indicated in the caption because the specimen was measured at mid-focus, and then refocused on surface ornament for the image, or because an obvious tear was discounted when the specimen was measured. Photographs were taken using differential interference contrast.

Few of the commonly occurring taxa are illustrated here, but illustrations of many may be found in White and Ager (1994).

# Plate 1

Figure 1. *Desmidiospora* sp., polar and equatorial axis: 26 µm and 20 µm, GSC 132005 (*see* the illustration in Kalgutkar and Jansonius (2000, Pl. 2, fig. 22, 23)), C-400716, depth: 935.78 m, P4364-22, England Finder Co-ordinate: E49/3.

Figure 2. *Inapertisporites pisciculatus* (Norris) Kalgutkar and Jansonius 2000, polar and equatorial axis: 34 µm and 24 µm, GSC 132006. The probable *Inapertisporites pisciculatus* is like Norris' illustration (1997, Pl. 2, fig. 1–8), but these specimens do not have notable pores. C-400765, depth: 1070 m, P4364-90, England Finder Co-ordinate: G44/2.

Figure 3. Mallik2L-38 unknown 13, single longest visible dimension: 29 µm, GSC 132007. This fungal palynomorph has subquadrangular cells, each about 4 µm in diameter, arranged to yield a structure that is concave-triangular and di- or triprojectate. Each projection is made up of two rows of cells, terminating in a blunt apex. One broken apparent projection may be an attachment to another body. C-400654, depth: 886.38–886.39 m, P4364-1, England Finder Co-ordinate: K42/2.

Figure 4. Mallik2L-38 unknown 26, polar and equatorial axis: 52 µm and 36 µm, GSC 132008. This is probably a fungal palynomorph, ovoid with a prominent ridge, possibly a fold, and with an irregular, vermiculate surface pattern. C-400764, depth: 1060 m, P4364-89, England Finder Co-ordinate: O45/3.

Figure 5. Mallik2L-38 unknown 2, polar and equatorial axis: 34 µm and 21 µm, GSC 132009. This elongated, probable fungal spore is perforated by fine, evenly distributed foveolae. There appears to be an attachment scar near one pole. C-400584, depth: 112.45–112.47 m, P4364-38, England Finder Co-ordinate: G49/3.

Figure 6. *Striadiporites inflexus* (Ke and Shi) Norris 1986, polar and equatorial axis: 34 µm and 20 µm, GSC 132010. *See* the illustration *Striadiporites inflexus* (Ke et Shi ex Sung et al.) Norris 1986, p. 21, Pl. 1, fig. 30, 31, 35. C-400763, depth: 1050 m, P4364-88, England Finder Co-ordinate: U59/1.

Figure 7. *Striadiporites inflexus* (Ke and Shi) Norris 1986, polar and equatorial axis: 36 µm and 19 µm, GSC 132011, C-400764, depth: 1060 m, P4364-89, England Finder Co-ordinate: J65.

Figure 8. *Stereisporites microgranulus* Krutzsch 1963, single longest visible dimension: 26 µm, GSC 132012. *Sensu* Norris, 1986, Pl. 7, fig. 5–7. C-400648, depth: 830 m, P4364–65, England Finder Co-ordinate: S61.

Figure 9. *Baculatisporites comaumensis* (Cookson) Potonié 1956, single longest visible dimension: 34 µm, GSC 132013. *See* Norris, 1986, p. 32, Pl. 7, fig. 15. C-400759, depth: 1010 m, P4364-84, England Finder Co-ordinate: V53/1.

Figure 10. *Baculatisporites primarius primarius* Krutzsch 1967, single longest visible dimension: 44 µm, GSC 132014. *Baculatisporites primarius primarius* spores are trilete with quite robust, sparse, irregular baculate-verrucate ornament (Krutzsch, 1967, p. 54, Pl. 9). *Osmunda* spp. are similar, but as used here, the name applies to trilete spores with an irregular, but less robust baculate-verrucate ornament about 2–3 µm high. C-400730, depth: 943.72–943.74 m, P4364-27, England Finder Co-ordinate: E57.

Figure 11. *Baculatisporites primarius primarius* Krutzsch 1967, single longest visible dimension: 44 µm, GSC 132015, C-400752, depth: 960 m, P4364-79, England Finder Co-ordinate: G49.

Figure 12. *Baculatisporites crassiprimarius* (Krutzsch) Norris 1986, single longest visible dimension: 56 µm, GSC 132016. Note raised laesurae, and ornament of imbricated, irregular margined ridges. This is close to Krutzsch's (1967, p. 58) specimen, but not a perfect match as his ornament is more verrucate and irregularly distributed. C-400641, depth: 760 m, P4364-58, England Finder Co-ordinate: X59.

Figure 13a. (proximal), 13b (amb). *Baculatisporites crassiprimarius* (Krutzsch) Norris 1986, single longest visible dimension: 58 µm, GSC 132017, C-400643, depth: 780 m, P4364-60, England Finder Co-ordinate: D61/2.

Figure 14. *Baculatisporites quintus* (Thompson and Pflug) Krutzsch 1967, single longest visible dimension: 48 µm, GSC 132019. *See* Krutzsch (1967, p. 48). *See also* Norris (1986, p. 32, Pl. 7, fig. 23, 24). The exine of this spore is about 2 µm thick, below the ornament. The verrucae are subangular in plan view. C-400644, depth: 785 m, P4364-61, England Finder Co-ordinate: Q53/3.

Figure 15. *Baculatisporites crassiprimarius* (Krutzsch) Norris 1986, single longest visible dimension: 64 µm, GSC 132018, C-400726, depth: 939.05–939.07 m, P4364-26, England Finder Co-ordinate: U59/3.

Figure 16. *Baculatisporites quintus* (Thompson and Pflug) Krutzsch 1967, single longest visible dimension: 54 µm, GSC 132020. *Sensu* Norris (1986, p. 32, Pl. 7, fig. 23, 24). This is a round spore with a dense baculate-gemmate ornament. C-400752, 960 m, P4364-79, England Finder Co-ordinate: F65/4.

Figure 17. *Cicatricosisporites paradorogensis* Krutzsch 1959, single longest visible dimension: 46 µm, GSC 132021. *See* Krutzsch (1967, p. 80, Pl. 22, no. 7–12). C-400758, depth: 1000 m, P4364-83, England Finder Co-ordinate: D58.


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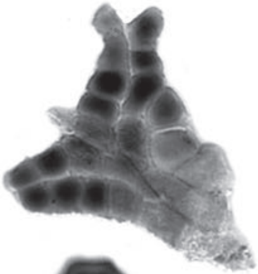
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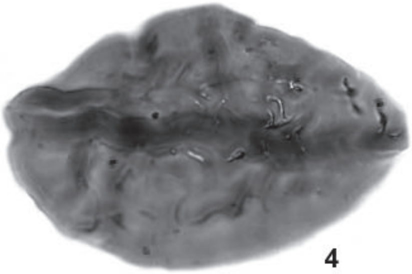
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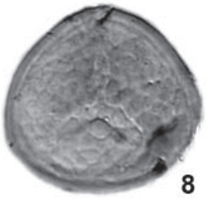
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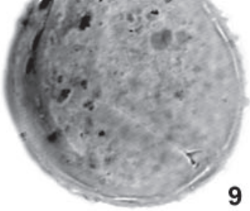
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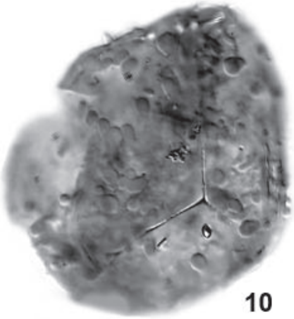
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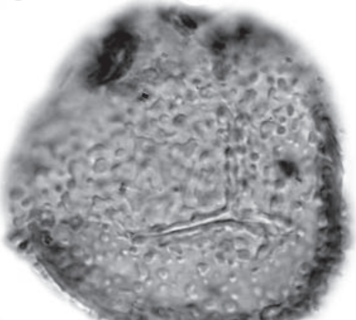
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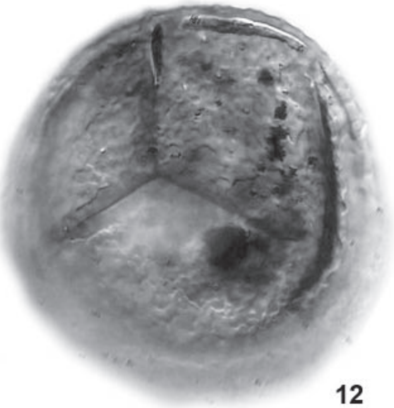
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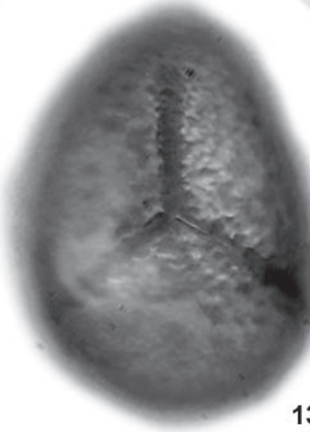
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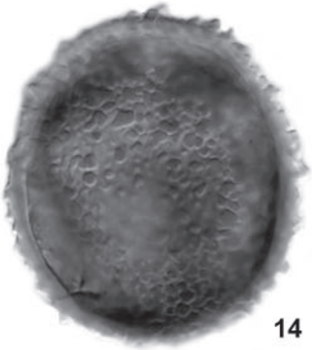
13b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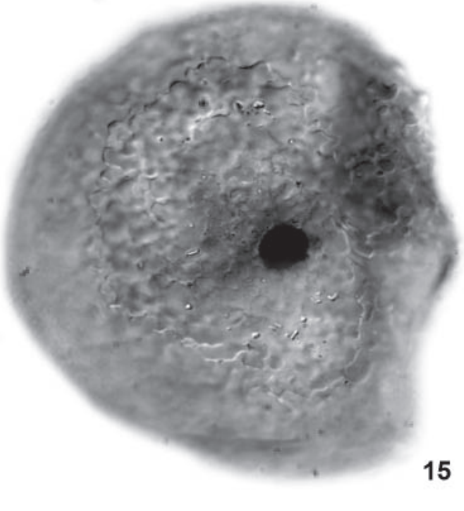
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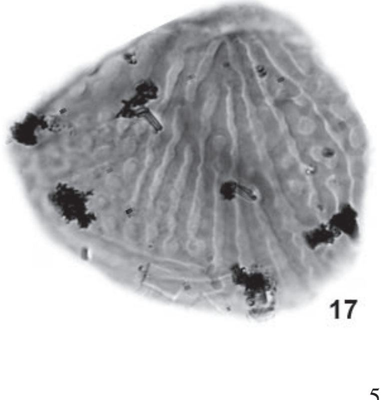
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# Plate 2

Figure 1a. (proximal), 1b (amb and apices). *Concavisporites* sp., single longest visible dimension: 32 µm, GSC 132022. This thick-walled trilete spore has low, broad verrucate ornament, reduced near the laesurae, and with the apices turned up toward the proximal pole. C-400758, depth: 1000 m, P4364-83, England Finder Co-ordinate: G58/3.

Figure 2. Mallik2L-28 unknown 18, polar and equatorial axis: 48 µm and 38 µm, GSC 132024. This specimen is monolete to inaperturate or with an erose area and with psilate surface having irregular granules to pits and an exine about 1 µm thick. C-400716, depth: 935.78 m, P4364-22, England Finder Co-ordinate: X59.

Figure 3. Mallik2L-38 unknown 14, single longest visible dimension: 38 µm, GSC 132025. This trilete spore has distinct laesurae, with irregularly distributed verrucate, baculate to gemmate ornament even on the margins of the laesurae. C-400660, depth: 890.71–890.72 m, P4364-2, England Finder Co-ordinate: R58.

Figure 4. *Osmunda irregulites* Martin and Rouse 1966, single longest visible dimension: 46 µm, GSC 132023. This specimen is crushed. The central proximal area is relatively unornamented with a faint raised trilete mark. Dense and irregular baculate-clavate ornament, about 3 µm high, covers the distal and equatorial areas, and equatorial area of the proximal pole. In type of ornament, it is similar to *Osmunda irregulites* of Martin and Rouse (1966, Pl. IV, fig. 29, 30). C-400743, depth: 948.15–948.17 m, P4364-32, England Finder Co-ordinate: O38/2.

Figure 5. Mallik2L-38 unknown 17, single longest visible dimension: 70 µm, GSC 132026. This is a trilete spore with a proximal, eroded vermiculate pattern and a distal verrucate-gemmate pattern. C-400709, depth: 928.00–928.02 m, P4364-20, England Finder Co-ordinate: R38/2.

Figure 6. Mallik2L-38 unknown 8, single longest visible dimension: 20 µm, GSC 132027. This small trilete spore has raised laesurae, baculate to rounded echinate ornament both proximally and distally. C-400643, depth: 780 m, P4364-60, England Finder Co-ordinate: H40.

Figure 7. Mallik2L-38 unknown 1, single longest visible dimension: 24 µm, GSC 132028. A subtriangular area indicates a possibly trilete mark on this specimen, ornamented by distinct gemmae and/or clavae on the proximal face, which are not visible on amb or distal face. C-400584, depth: 112.45–112.47 m, P4364-38, England Finder Co-ordinate: L47/3.

Figure 8. *Osmunda regalis*, single longest visible dimension: 42 µm, GSC 132029. Note the loosely spaced baculate to denticulate ornament on this specimen. *See* McAndrews et al. (1973, Fig. 19b, c). C-400643, depth: 780 m, P4364-60, England Finder Co-ordinate: P67/2.

Figure 9. *Retitriletes* sp., single longest visible dimension: 38 µm, GSC 132032. This trilete spore has a coarse distal reticulum with muri running dominantly toward the equator, following Norris (1986). C-400648, depth: 830 m, P4364-65, England Finder Co-ordinate: L57.

Figure 10. *Osmundacidites wellmanii* Couper 1953, single longest visible dimension: 76 µm, GSC 132030. This has the discrete verrucate and/or baculate and/or subgemmate ornament of *Osmunda* sp. (e.g. McAndrews et al., 1973, Fig. 19). It compares with Norris' (1986, Pl. 7, fig. 11, p. 31) illustration of *Osmundacidites wellmanii* Couper 1953. C-400645, depth: 800 m, P4364-62, England Finder Co-ordinate: R65/4.

Figure 11. Polypodiaceae-Dennstaedtiaceae, single longest visible dimension: 38 µm, GSC 132031. This monolete spore is similar to Polypodiaceae-Dennstaedtiaceae Form 1 of Martin and Rouse (1966, Pl. III, fig. 19, 20). C-400643, depth: 780 m, P4364-60, England Finder Co-ordinate: O44.

Figure 12a. (proximal), b (distal). *Retitriletes* sp. cf. *R. novomexicanus* of Norris (1986), single longest visible dimension: 45 µm, GSC 132033. *Retitriletes* sp. cf. *R. novomexicanus* has been used following Norris' nomenclature for *Lycopodium* spores where the reticulum is distally elongated and discontinuous (Norris, 1986, Pl. 8, fig. 3, 4, p. 33). The reticulum may be reduced or absent proximally; however, Anderson's description and illustration (1960, p. 14, Pl. 1, fig. 2; Pl. 8, fig. 1) of *Lycopodium novomexicanum* does not show the same discontinuous reticulum. C-400753, depth: 970 m, P4364-80, England Finder Co-ordinate: N65/4.

Figure 13. *Verrucatosporites favus* (Potonié) Thompson and Pflug 1953, polar and equatorial axis: 38 µm and 30 µm, GSC 132034. Spores with a patellate ornament compare favourably with *Verrucatosporites favus* (Potonié) Thompson and Pflug 1953 as illustrated by Norris (1986, p. 34, Pl. 8, fig. 11, 12). C-400644, depth: 785 m, P4364-61, England Finder Co-ordinate: T38/4.

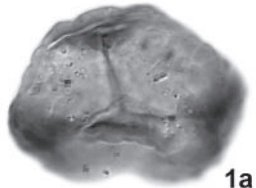
Figure 14. *Verrucatosporites favus* (Potonié) Thompson and Pflug 1953, polar and equatorial axis: 36 µm and 26 µm, GSC 132035, C-400765, depth: 1070 m, P4364-90, England Finder Co-ordinate: E38/4.

Figure 15. *Ephedra* sp., polar and equatorial axis: 42 µm and 20 µm, GSC 132036. This pollen is similar to the polyplicate *Ephedra* pollen illustrated by Moore and Webb (1978, Pl. 30f). C-400734, depth: 944.31–944.33 m, P4364-28, England Finder Co-ordinate: Q40/4.

Figure 16. *Podocarpus*-type, polar and equatorial axis: 54 µm and 40 µm, GSC 132037. This specimen has a small capa and large bladders with the reticular ridges radiating from the colpal region, as shown by Erdtman (1957, Fig. 61a). C-400698, depth: 921.38–921.40 m, P4364-17, England Finder Co-ordinate: H38/2.

Figure 17. *Sciadopitys* sp., single longest visible dimension: 36 µm, GSC 132038. The columellae are visible in the vellum of this pollen, as shown by Shimakura (1973, Pl. 7, fig. 35, 36). C-400652, depth: 870 m, P4364-69, England Finder Co-ordinate: H47/3.

PLATE 2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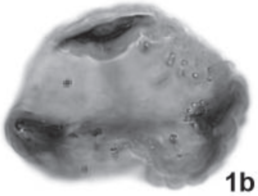
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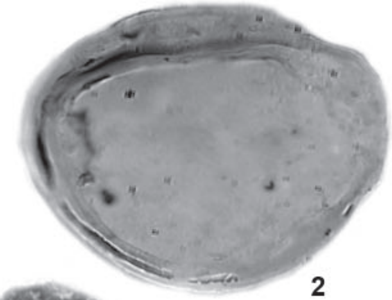
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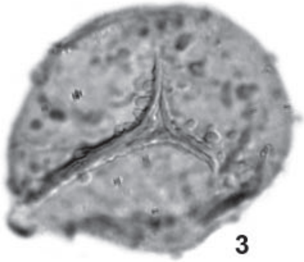
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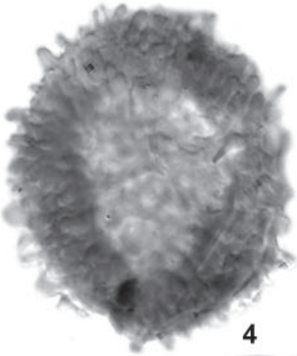
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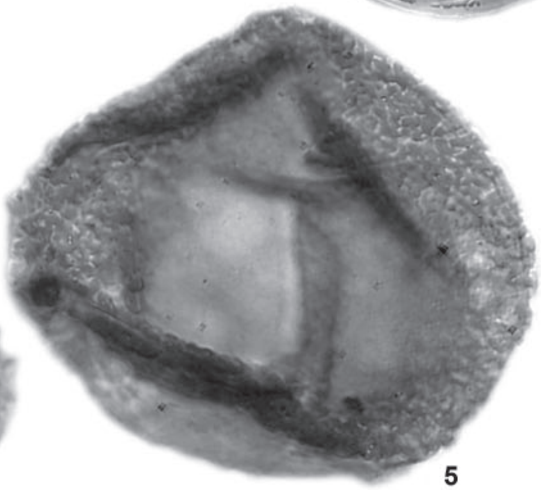
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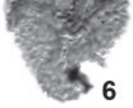
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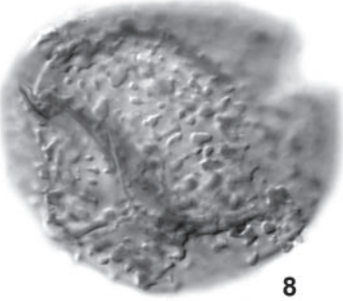
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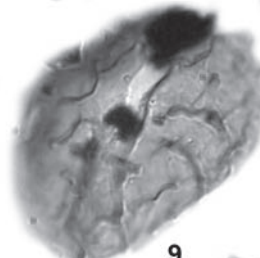
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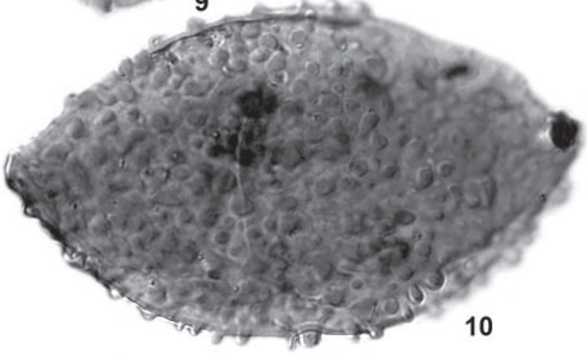
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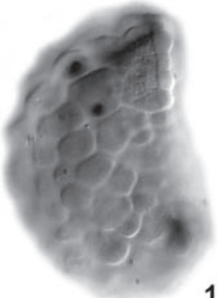
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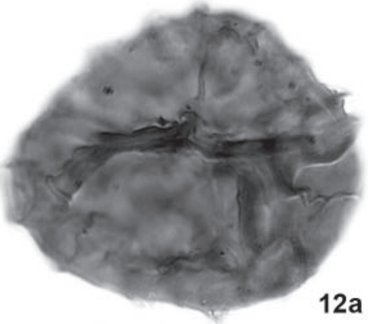
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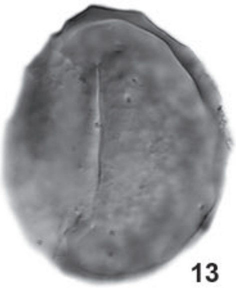
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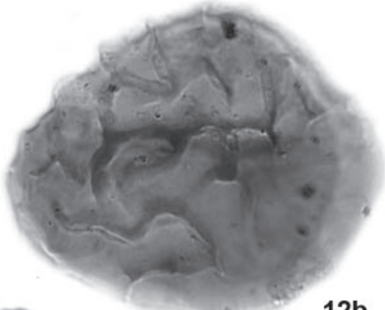
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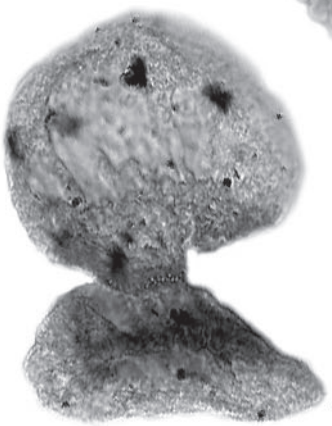
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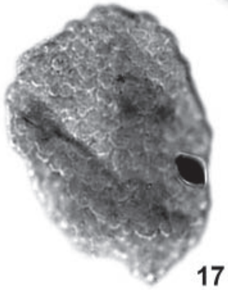
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# Plate 3

Figure 1. Taxodiaceae-Cupressaceae-Taxaceae, single longest visible dimension: 30 μm, GSC 132039. *See* the discussion of this morphotype in White and Ager (1994, Pl. 2, fig. 5). C-400584, depth: 112.45–112.47 m, P4364-38, England Finder Co-ordinate: S40/4.

Figure 2. Mallik2L-38 unknown 23, single longest visible dimension: 33 μm, GSC 132040. This palynomorph is mono- or disulcate, shaped like a *Tsuga* grain, and has possible minor projections at the (?)equator, and a foveolate exine. C-400743, depth: 948.15–948.17 m, P4364-32, England Finder Co-ordinate: U46.

Figure 3. *Tsuga* sp., single longest visible dimension: 42 μm, GSC 132041. Pollen grains recorded as *Tsuga* sp. include this morphotype, a compact grain about 40 μm in diameter. C-400638, depth: 730 m, P4364-55, England Finder Co-ordinate: L36/2.

Figure 4. *Pinus koraiensis*-type, polar and equatorial axis: 60 μm and 44 μm, GSC 132042. Note the *Picea*-like shape and verrucae between bladders, as described by White and Ager (1994, Pl. 2, fig. 14, 16). C-400644, depth: 785 m, P4364-61, England Finder Co-ordinate: S63/1.

Figure 5. Cyperaceae, polar and equatorial axis: 30 μm and 30 μm, GSC 132043. These subtriangular grains with thin exines and erose pseudo-pores are typical of the Cyperaceae (Kapp et al., 2000). C-400584, depth: 112.45–112.47 m, P4364-38, England Finder Co-ordinate: W38/2.

Figure 6. *Momipites wyomingensis*?, single longest visible dimension: 31 μm, GSC 132044. This triporate grain has an erose endopore and polar elongation of the pore, although the protrusion of the pore is not similar to the illustration of Nichols and Ott (1978, Pl. 1, fig. 1–4). C-400642, depth: 770 m, P4364-59, England Finder Co-ordinate: L67/2.

Figure 7. *Labrapollis* sp., single longest visible dimension: 22 μm, GSC 132045. This taxon is triporate and has polar plicae with the folds oriented between the pores. *See* Krutzsch (1968). C-400737, depth: 945.20–945.22 m, P4364-29, England Finder Co-ordinate: Q36/2.

Figure 8. *Sparganium* sp., polar and equatorial axis: 30 μm and 18 μm, GSC 132046. Note the pore on the amb and the fine reticulation, as illustrated by Kapp et al. (2000). C-400641, depth: 760 m, P4364-58, England Finder Co-ordinate: T53/4.

Figure 9. *Annutriporites* sp. A of Norris (1986), single longest visible dimension: 20 μm, GSC 132047. This triporate specimen has the annular thickenings around the pores of *Annutriporites* sp. A. of Norris (1986, Pl. 10, fig. 20–23, p. 39). C-400764, depth: 1060 m, P4364-89, England Finder Co-ordinate: U46/4.

Figure 10. *Boisduvalia clavatites* Piel 1971, single longest visible dimension: 52 μm, GSC 132048. This tetrad has clavate ornamented, as illustrated by Piel (1971, Pl. XV, fig. 141). C-400730, depth: 943.72–943.74 m, P4364-27, England Finder Co-ordinate: N53/3.

Figure 11. *Diervilla* of McIntyre (1991), single longest visible dimension: 51 μm, GSC 132049. This is a large triporate grain with baculate ornament, similar to that illustrated by McIntyre (1991, Pl. 4, fig. 1, 2) as *Diervilla*. In ornament, it is very similar to Triporate B of Piel, 1971 (p. 1914, Pl. XVII, fig. 150), but the pores differ from Triporate B. The protruding, thickened and colpoid pore morphology of this specimen is exhibited by *Ludwigia*, of Onagraceae (Praglowski et al., 1983, Pl. 10, 11), and it seems that this pollen more likely belongs in Onagraceae than the Caprifoliaceae, as implied by the name *Diervilla*; however, “Diervilla of McIntyre (1991)” is used to compare this specimen to his specimen. C-400737, depth: 945.20–945.22 m, P4364-29, England Finder Co-ordinate: G58/1.

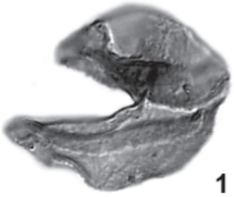
Figure 12. *Ostrya* or *Carpinus*, single longest visible dimension: 34 μm, GSC 132051. This specimen is tetraporate, without endexinal separation at the pores. Lieux (1980b, p. 211, 212) discussed the occurrence of tetraporate grains in *Ostrya* and *Carpinus*. Likely many more triporate grains of these genera occur, but were not separately identified. C-400638, depth: 730 m, P4364-55, England Finder Co-ordinate: H63/2.

Figure 13. *Polyvestibulopollenites trinus* (Stanley) Norris 1986, single longest visible dimension: 24 μm, GSC 132050. This specimen compares well with *Polyvestibulopollenites trinus* (Stanley) Norris 1986 (Pl. 10, fig. 46, p. 41). C-400764, depth: 1060 m, P4364-89, England Finder Co-ordinate: J43/1.

Figure 14. cf. *Planera*, polar and equatorial axis: 22 μm and 18 μm, GSC 132053. The pores of this grain are slightly annulate with apparent arcoid streaks between the pores, suggesting *Planera* (Erdtman, 1966; Kapp et al., 2000). C-400611, depth: 118.05–118.07 m, P4364-44, England Finder Co-ordinate: H42/4.

Figure 15. Caryophyllaceae, single longest visible dimension: 28 m, GSC 132054. See illustrations in McAndrews et al. (1973, Fig. 8c) and Kapp et al. (2000). C-400611, depth: 118.05–118.07 m, P4364-44, England Finder Co-ordinate: U38/4.

Figure 16. Chenopodiineae, single longest visible dimension: 18 m, GSC 132055. See illustrations in McAndrews et al. (1973, Fig. 8f) and Kapp et al. (2000). C-400611, depth: 118.05–118.07 m, P4364-44, England Finder Co-ordinate: U70.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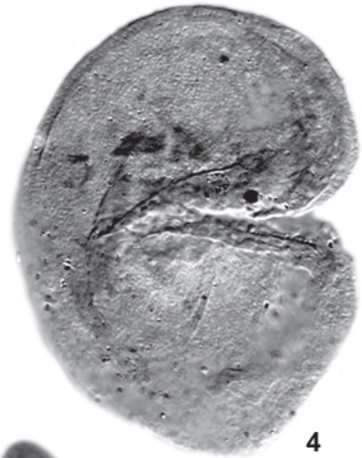
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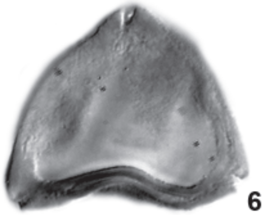
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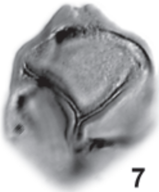
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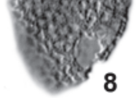
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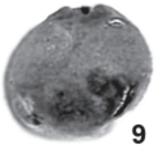
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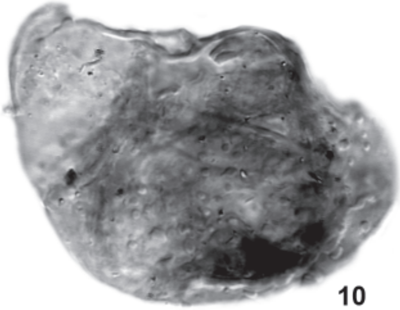
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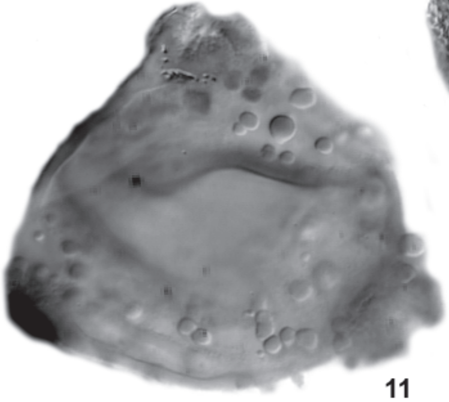
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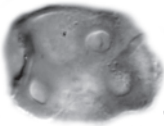
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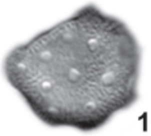
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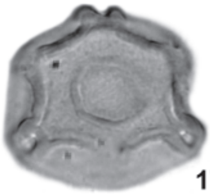
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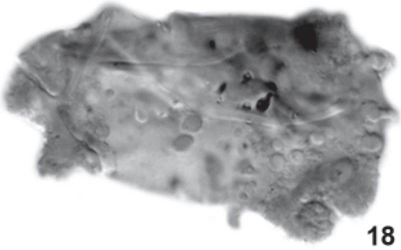
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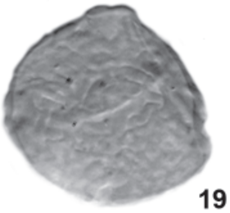
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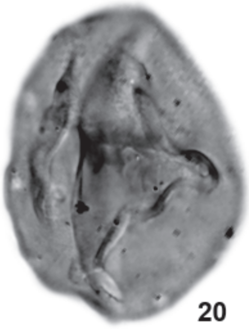
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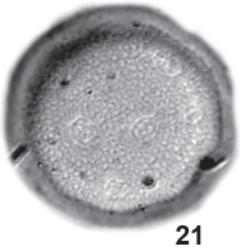
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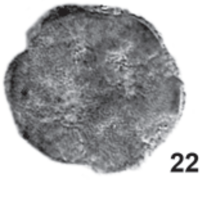
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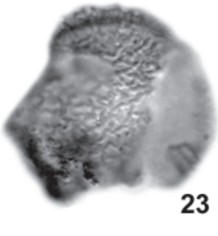
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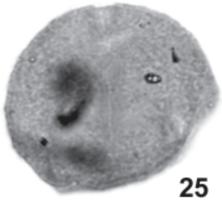
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## Plate 3 (cont.)

Figure 17. *Paraalnipollenites alterniporus* (Simpson) Srivastava 1975, single longest visible dimension: 28 m, GSC 132056. See the discussion in Srivastava (1975, p. 140). C-400660, depth: 890.71–890.72 m, P4364-2, England Finder Co-ordinate: H55/3.

Figure 18. *Diervilla* of McIntyre (1991), single longest visible dimension: 52 µm, GSC 132052, C-400772, depth: 1140 m, P4364-97, England Finder Co-ordinate: E50/1.

Figure 19. *Ulmus*-type, single longest visible dimension: 28 µm, GSC 132057. This is a tetraporate grain with a rugulate ornament (*see* White and Ager, 1994). C-400635, depth: 700 m, P4364-52, England Finder Co-ordinate: O59.

Figure 20. *Juglans* sp., single longest visible dimension: 42 µm, GSC 132058. This is a porate, heteropolar grain, as illustrated by Bassett et al. (1978, p. 202–204). C-400759, depth: 1010 m, P4364-84, England Finder Co-ordinate: K42/4.

Figure 21. *Liquidambar* sp., single longest visible dimension: 31 µm, GSC 132059. This grain compares well with *Liquidambar stryraciflua*, illustrated by Lieux (1980b, Pl. XXV, fig. 1–6), in having a microreticulate and/or perforate exine and granulae in the pores. C-400648, depth: 830 m, P4364-65, England Finder Co-ordinate: R51/1.

Figure 22. *Liquidambar*? sp., single longest visible dimension: 24 µm, GSC 132060. This grain is questionably compared to *L. stryraciflua* (Lieux, 1980b, Pl. XXV, fig. 1–6). The pores are not as distinctly developed, and the pore granulae are not clear in this specimen, but this morphology falls in the range of *Liquidambar* spp., as illustrated by Kuprianova (1959, Pl. 1) . C-400773, depth: 1150 m, P4364-98, England Finder Co-ordinate: M55.

Figure 23. Brassicaceae (Cruciferae), single longest visible dimension: 28 µm, GSC 132061. This very robust tricolpate grain has coarse rugu-reticulate, intectate surface ornament formed by fusion of the heads of clavae. The exine is about 2 µm thick and intine about 2 µm thick (*see* Erdtman, 1966; Kapp et al., 2000). C-400634, depth: 690 m, P4364-51, England Finder Co-ordinate: O37/1.

Figure 24. *Ribes* sp., single longest visible dimension: 15 µm, GSC 132062. *See* the illustration of *Ribes* spp. in Adams and Morton (1974, Pl. 22). C-400580, depth: 111.55–111.57 m, P4364-37, England Finder Co-ordinate: H51/1.

Figure 25. *Fagus* sp., single longest visible dimension: 28 µm, GSC 132063. This is a tricolporate grain, with semitectate ornament (*see* Lieux, 1980b, Pl. XXXVIII) discussed in White and Ager (1994, Pl. 5, fig. 9). C-400765, depth: 1070 m, P4364-90, England Finder Co-ordinate: N44/4.

## Plate 4

Figure 1. Caprifoliaceae, single longest visible dimension: 42 µm, GSC 132064. This is a crushed grain that appears to have three colpi. It is tectate with spares spinulose ornament 1 µm high or less, with the columellae giving the exine a verrucate appearance below the spinulae. It most likely belongs in Caprifoliaceae. C-400772, depth: 1140 m, P4364-97, England Finder Co-ordinate: P49/3.

Figure 2. *Fagus* sp., polar and equatorial axis: 32 µm and 30 µm, GSC 132065, C-400730, depth: 943.72–943.74 m, P4364-27, England Finder Co-ordinate: X53/3.

Figure 3. *Diervilla echinata* Piel 1971, single longest visible dimension: 52 µm, GSC 132066. *See* the illustration in Piel (1971, Pl. XVI, fig. 144, 145, p. 1916). C-400639, depth: 740 m, P4364-56, England Finder Co-ordinate: N45.

Figure 4. *Jussiaea* or *Ludwigia*, single longest visible dimension: 35 µm, GSC 132067. *See* the illustration in Piel (1971, Pl. XVII, fig. 152, 153. p. 1914). *Jussiaea* was combined under *Ludwigia* (Brown, 1967). C-400644, depth: 785 m, P4364-61, England Finder Co-ordinate: P55.

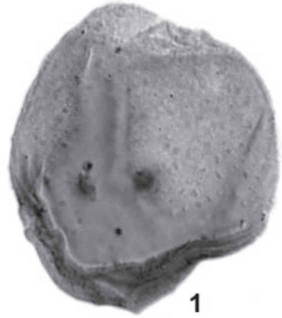
Figure 5. *Lonicerapollis gallwitzii*?, single longest visible dimension: 40 µm, GSC 132068. This grain is compressed in the polar axis, and compares in ornament with Norris' illustration (1997, Pl. 6, fig. 30), although it does not exhibit a thick, columellate exine. C-400672, depth: 897.35–897.37 m, P4364-7, England Finder Co-ordinate: H43/3.

Figure 6. Mallik2L-38 unknown 3, polar and equatorial axis: 23 µm and 18 µm, GSC 132069. This tricolpate grain has a 4 µm thick, nearly tectate exine, having a very fine reticulum with luminae less than 1 µm. Scabrae are apparently present on the tectum. C-400588, depth: 113.26–113.28 m, P4364-39, England Finder Co-ordinate: G46/3.

Figure 7. *Lonicerapollis gallwitzii* Krutzsch 1962, polar and equatorial axis: 32 µm and 32 µm, GSC 132070. This grain is similar in exine structure and ornament to Norris' illustration (1997, Pl. 6, fig. 30–32). C-400769, depth: 1110 m, P4364-94, England Finder Co-ordinate: K40/2.

Figure 8. Mallik2L-38 unknown 15, single longest visible dimension: 26 µm, GSC 132072. This is a tricol(por?)ate grain with colpi almost reaching the poles. The colpi have a margo, apparently torn at equator, possible indicating a pore. The exine is 1 µm thick exine on intercolpium, with scabrate ornament and faintly visible columellae. C-400682, depth: 903.34–903.36 m, P4364-11, England Finder Co-ordinate: J55/3.

PLATE 4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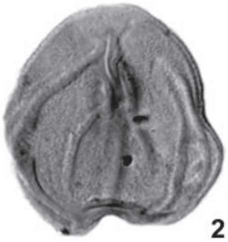
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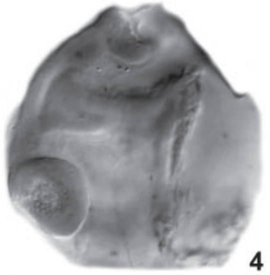
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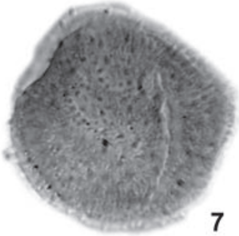
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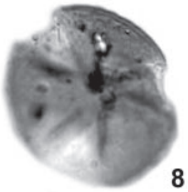
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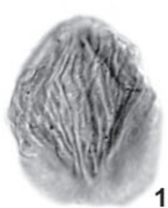
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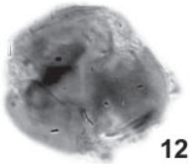
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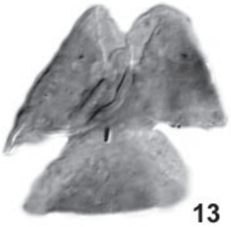
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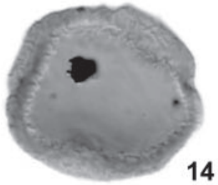
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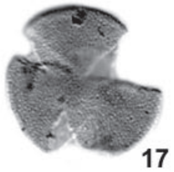
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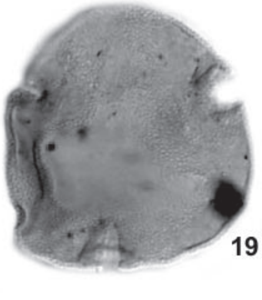
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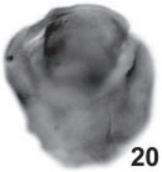
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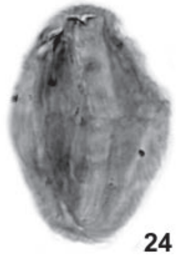
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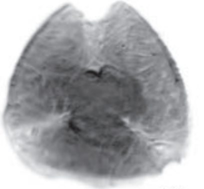
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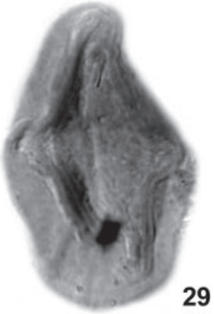
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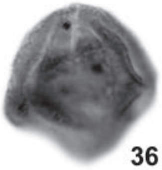
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# Plate 4 (cont.)

Figure 9. Mallik2L-38 unknown 11, polar and equatorial axis: 16 μm and 12 μm, GSC 132073. This is a small tricolpate pollen grain, tectate and with a microreticulum of even-sized lumina. C-400649, depth: 840 m, P4364-66, England Finder Co-ordinate: X61.

Figure 10. Mallik2L-38 unknown 19, polar and equatorial axis: 26 μm and 20 μm, GSC 132074. This tricolporate specimen has a geniculus in the colpus, suggesting the presence of an erupted pore, and a polar-oriented, partly anastomosing, coarse striate ornament. It may belong to Rosaceae. C-400719, depth: 936.32–936.33 m, P4364-23, England Finder Co-ordinate: W43.

Figure 11. Mallik2L-38 unknown 4, polar and equatorial axis: 14 μm and 12 μm, GSC 132071. This is a small tricolpate grain with gaping furrows about half the length of the grain, and is ornamented with clavae. C-400596, depth: 114.90–114.92 m, P4364-41, England Finder Co-ordinate: T46/2.

Figure 12. Mallik2L-38 unknown 24, single longest visible dimension: 23 μm, GSC 132075. This appears to be an oblate, tricolpate grain with scabrate ornament and with a tectum composed of clavae. C-400745, depth: 949.20–949.22 m, P4364-33, England Finder Co-ordinate: P38/2.

Figure 13. Mallik2L-38 unknown 28, single longest visible dimension: 32 μm, GSC 132076. This tricolpate grain in known only from one polar presentation. The exine is thin and apparently semitectate, with pilae less that 0.5 μm high, fusing to give a psilate or microfoveolate exine. The tectum appears to be reduced toward the colpi, an appearance enhanced by oblique compression of the grain. The colps have irregular margins. It is similar (in morphology) to *Cranwellia* sp., illustrated by Nichols and Sweet (1993, Pl. II, fig. 3), but not in striate sculpture. It may be reworked from Campanian or Maastrichtian rocks. C-400770, depth: 1120 m, P4364-95, England Finder Co-ordinate: G38.

Figure 14. Mallik2L-38 unknown 22, single longest visible dimension: 26 μm, GSC 132077. This is apparently an oblate grain with two pores visible at 12 o'clock and 3 o'clock and it may be stephanoporate. It has a thick, undifferentiated exine (1.5 μm) and a discontinuous, faint reticulum. C-400739, depth: 946.20–946.22 m, P4364-30, England Finder Co-ordinate: E36/2.

Figure 15. *Pistillipollenites macgregorii* Rouse 1962, single longest visible dimension: 24 μm, GSC 132078. *See* the illustration in Rouse (1962, Pl. 1, fig. 8–12). C-400758, depth: 1000 m, P4364-83, England Finder Co-ordinate: D47.

Figure 16. *Pistillipollenites macgregorii* Rouse 1962, single longest visible dimension: 24 μm, GSC 132079, C-400758, depth: 1000 m, P4364-83, England Finder Co-ordinate: T64/3.

Figure 17. *Fraxinus* sp., single longest visible dimension: 23 μm, GSC 132080. This grain is small, tricolpate, intectate and finely reticulate, similar to *Fraxinus nigra* (Bassett et al., 1978, p. 213–214). C-400666, depth: 892.50–892.52 m, P4364-4, England Finder Co-ordinate: P46/2.

Figure 18a, 18b. Mallik2L-38 unknown 30, polar and equatorial axis: 42 μm and 26 μm, GSC 132081. This is a tricolpate grain with a distinct 3 μm thick exine, half of which is foot layer, half strongly columellate ektexine, with a thick tectum. The tectum is apparently psilate, but the intercolpal areas show a slightly linear, strong verrucate pattern, which must be produced by the thick columellae. C-400772, depth: 1140 m, P4364-97, England Finder Co-ordinate: H47/3.

Figure 19. *Tilia*-type, single longest visible dimension: 38 μm, GSC 132082. *Tilia*-type is discussed in White and Ager (1994, p. 72, Pl. 5, fig. 25). C-400750, depth: 951.28–951.30 m, P4364-35, England Finder Co-ordinate: S41/3.

Figure 20. *Psilastephanocolpites* cf. *marginatus* of Norris (1997), single longest visible dimension: 22 μm, GSC 132083. This specimen is tetracolporate, virtually the same size, and has the faint, equatorially elongated, biconvex pore, seen on re-examination of the reference slide of Norris' specimen (1997, p. 39, Pl. 6, no. 34), called *Psilastephanocolpites* cf. *marginatus* Gonzales Guzman 1967. This grain is the same as with Tetracolporate B of Piel (1971, Pl. XII, fig. 93, 94). It appears that all colps do not project the same distance toward the pole, as in Norris' and Piel's illustrations, but some oblique compression may contribute to this appearance. C-400772, depth: 1140 m, P4364-97, England Finder Co-ordinate: M49/3.

Figure 21. *Psilastephanocolpites* cf. *marginatus* of Norris (1997), 23 μm and 20 μm, GSC 132084, C-400772, depth: 1140 m, P4364-97, England Finder Co-ordinate: U53/1.

Figure 22. *Castanea*-type, polar and equatorial axis: 16 μm and 8 μm, GSC 132085. *Castanea*-type is discussed in White and Ager (1994, p. 72, Pl. 5, fig. 7). C-400644, depth: 785 m, P4364-61, England Finder Co-ordinate: R36/2.

# Plate 4 (cont.)

Figure 23. *Psilastephanocolpites* cf. *marginatus* of Norris (1997), polar and equatorial axis: 26 µm and 24 µm, GSC 132086, C-400764, depth: 1060 m, P4364-89, England Finder Co-ordinate: M67/2.

Figure 24. *Acer* sp., polar and equatorial axis: 33 µm and 32 µm, GSC 132087. This is apparently a tricolpate grain, although a pore is suggested by an inflection in the colpus. A faint striate ornament runs in a general polar direction. It is similar to *Acer spicatum* (Adams and Morton, 1976, Pl. 41). C-400711, depth: 928.80–928.82 m, P4364-21, England Finder Co-ordinate: D51/3.

Figure 25. *Aceripollenites tener* (Samoilovitch) Norris 1997, single longest visible dimension: 26 µm, GSC 132088. This is an intectate, apparently oblate grain with deep colpi and a meridional striate pattern from pole to equator, and size similar to that shown by Norris (1997, p. 38, Pl. 5, fig. 22, 23). C-400734, depth: 944.31–944.33 m, P4364-28, England Finder Co-ordinate: D36/4.

Figure 26. Apiaceae (Umbelliferae), polar and equatorial axis: 22 µm and 12 µm, GSC 132089. This tricolporate grain has equatorially elongated pores and a thick tectate exine typical of the Apiaceae (Kapp et al., 2000). The exine is thickest at the poles, about 1.5 µm thick, and the tectum appears to be microreticulate. C-400638, depth: 730 m, P4364-55, England Finder Co-ordinate: G70/1.

Figure 27. *Castanea*-type, polar and equatorial axis: 14 µm and 9 µm, GSC 132090. This broken specimen appears to *Castanea*-type, as discussed in White and Ager (1994, p. 72), although it does not have sharply defined pores. C-400745, depth: 949.20–949.22 m, P4364-33, England Finder Co-ordinate: L47/3.

Figure 28. *Cornus* sp., polar and equatorial axis: 42 µm and 24 µm, GSC 132092. This specimen of *Cornus* sp. shows subangular shape and the verrucate ornament of *Cornus* spp. (McAndrews et al., 1973, Fig. 14a–c). C-400677, depth: 900.62–900.64 m, P4364-9, England Finder Co-ordinate: F40/3.

Figure 29. *Cornus* sp., polar and equatorial axis: 42 µm and 28 µm, GSC 132091. This large tricolporate grain has the strongly erupted pores and subangular shape of *Cornus* sp. (McAndrews et al., 1973, Fig. 14a–c), but no pronounced verrucate pattern. C-400660, depth: 890.71–890.72 m, P4364-2, England Finder Co-ordinate: V61.

Figure 30. *Ilex*-type, single longest visible dimension: 20 µm, GSC 132093. *Ilex*-type is discussed in White and Ager (1994, p. 73, Pl. 5, fig. 14). C-400643, depth: 780 m, P4364-60, England Finder Co-ordinate: V7.

Figure 31. Mallik2L-38 unknown 5, polar and equatorial axis: 24 µm and 16 µm, GSC 132094. The pores in this tricolporate grain appear to be equatorially elongated. The exine is tectate and scabrate and thickest (about 3 µm) at the poles. C-400634, depth: 690 m, P4364-51, England Finder Co-ordinate: V36/4.

Figure 32. Mallik2L-38 unknown 6, polar and equatorial axis: 19 µm and 11 µm, GSC 132095. This specimen is tricolporate with apparent equatorial elongation of pores, and is tectate with scabrate and/or verrucate ornament. C-400639, depth: 740 m, P4364-56, England Finder Co-ordinate: N66/1.

Figure 33. Mallik2L-38 unknown 9, polar and equatorial axis: 19 µm and 14 µm, GSC 132096. This grain is tricolporate with a robust exine. It is tectate with clearly visible columellae and an exine up to 2 µm thick at poles, but thinner at equator. The ornament is scabrate. C-400644, depth: 785 m, P4364-61, England Finder Co-ordinate: X53/3.

Figure 34. Mallik2L-38 unknown 10, single longest visible dimension: 24 µm, GSC 132097. This is grain is apparently oblate, with distinct colps reaching 3/4 way to the pole, distinct pores, and a tectate, microreticulate exine. C-400648, depth: 830 m, P4364-65, England Finder Co-ordinate: E59/4.

Figure 35. Mallik2L-38 unknown 12, polar and equatorial axis: 22 µm and 16 µm, GSC 132098. This is a tricolporate pollen grain with sharply erupted pores, scabrate ornament, and a very robust exine about 1.5 µm to 2 µm thick. It is similar to the Plate 5, figure 1 grain, except for the pronounced eruption of the pores in this specimen, that may be a result of the crushing of the grain. C-400653, depth: 880 m, P4364-70, England Finder Co-ordinate: J47.

Figure 36. Mallik2L-38 unknown 12, polar and equatorial axis: 24 µm and 22 µm, GSC 132099. This specimen of Mallik2L-38 unknown 12 shows more verrucate ornament and a distinct, slit-like, psilate colpus. Other specimens measured in this slide range in size, i.e. polar and equatorial axis: 32 µm and 22 µm, 28 µm and 20 µm, 29 µm and 18 µm, and 24 µm and 22 µm. This range of sizes might indicate that this is a complex of pollen species. C-400684, depth: 903.81–903.83 m, P4364-12, England Finder Co-ordinate: J36/2.

# Plate 5

Figure 1. Mallik2L-38 unknown 12, polar and equatorial axis: 20 µm and 16 µm, GSC 132100. This specimen shows Mallik2L-38 unknown 12 undeformed, with pores not strongly erupted. C-400720, depth: 936.75–936.77 m, P4364-24, England Finder Co-ordinate: V40.

Figure 2. Mallik2L-38 unknown 21, polar and equatorial axis: 24 µm and 18 µm, GSC 132101. This is a tricolpate, tectate grain, apparently reticulate between the colpi and equatorially rugulate near the colpi, with a 3 µm thick exine thick. C-400734, depth: 944.31–944.33 m, P4364-28, England Finder Co-ordinate: K36/2.

Figure 3. Mallik2L-38 unknown 25, polar and equatorial axis: 24 µm and 14 µm, GSC 132102. This is a psilate, tricolporate grain with an indistinct pore, a subquadrangular shape, and an exine about 1.5 µm thick. It is similar to Mallik2L-38 unknown 12, except for its more subquadrangular shape and lack of an ornamented exine. C-400748, depth: 950.10–950.12 m, P4364-34, England Finder Co-ordinate: K44/4.

Figure 4. Mallik2L-38 unknown 27, polar and equatorial axis: 24 µm and 20 µm, GSC 132103. This is a tricolporate grain with small pores and colpi extending about 3/4 of the way toward the poles. The colps are marked by dark exine. The exine is consistently about 1–1.5 µm thick with faintly visible columellae. The exine is tectate and psilate, but also appears to be micro-foveolate in the intercolpal region. C-400766, depth: 1080 m, P4364-91, England Finder Co-ordinate: H49/3.

Figure 5. Mallik2L-38 unknown 31, polar and equatorial axis: 28 µm and 21 µm, GSC 132104. This tricolporate grain exhibits a geniculum at the pore, although this is probably exaggerated by some crushing in the polar axis. The exine is thick, about 2 µm, with a thick foot layer, a thin columellate layer, and a thin, psilate tectum. C-400773, depth: 1150 m, P4364-98, England Finder Co-ordinate: J68/3.

Figure 6. *Nyssa*? sp., polar and equatorial axis: 22 µm and 22 µm, GSC 132105. This specimen was identified as *Nyssa* sp., being comparable in morphology to *Nyssa aquatica* and *N. sylvatica*, as illustrated by Adams and Morton (1976, Pl. 46) and Lieux, (1983, p. 326, Pl. XCV, XCVI), but is considerably smaller than even the smaller *N. sylvatica* (polar and equatorial axis: about 30–37 µm and 30–35 µm). In retrospect, the microreticulate exine is not comparable with *Nyssa*, and this is perhaps another specimen of Mallik2L-38 unknown 10, illustrated above in Plate 4, figure 34. C-400638, depth: 730 m, P4364-55, England Finder Co-ordinate: P55/1.

Figure 7. *Nyssa*? sp., single longest visible dimension: 30 µm, GSC 132106. This oblique polar presentation shows the thickened to annulate pores, suggesting *Nyssa* (*see* Lieux, 1983, p. 326, Pl. XCV, XCVI). It has a thin columellate exine, is semitectate and microfoveolate and is in the right size range. It also shows strong similarities in polar presentation to *Alangium chinense* (Wang et al., 1995, Pl. 15, fig. 1), but is much smaller. Alangiaceae are related to Nyssaceae in Cornales (Heywood, 1978). C-400761, depth: 1030 m, P4364-86, England Finder Co-ordinate: O53.

Figure 8. *Quercus* sp., polar and equatorial axis: 22 µm and 16 µm, GSC 132107. This specimen has the irregular verrucate ornament of *Quercus*, and has an equatorial inflection which suggests the presence of a pore (*see* Adams and Morton, 1972, Pl. 15, 16; Bassett et al., 1978, p. 180–190). C-400592, depth: 113.95–113.97 m, P4364-40, England Finder Co-ordinate: S39/3.

Figure 9. *Quercus*? sp., polar and equatorial axis: 30 µm and 24 µm, GSC 132108. This tricolpate specimen seems similar to *Quercus* in being semitectate with visible columellae and having irregular verrucate ornament, as shown by Lieux (1980b, Pl. XXXIX–XLVI). C-400687, depth: 905.73–905.75 m, P4364-13, England Finder Co-ordinate: H52.

Figure 10. *Rhoipites* sp. cf. *R. microreticulatus*, polar and equatorial axis: 26 µm and 20 µm, GSC 132109. *Rhoipites* sp., cf. *R. microreticulatus* (Pflug and Thompson *in* Thompson and Pflug) Takahashi and Jux 1986 is illustrated by Norris (1997, p. 41, Pl. 5, fig. 26–28). The lumina of this reticulate, tricolporate specimen are about 1 µm, grading to microreticulate sizes at the colpus. The pore is equatorially elongated. C-400752, depth: 960 m, P4364-79, England Finder Co-ordinate: F51.

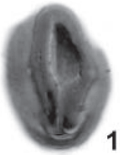
Figure 11. *Rhoipites* sp., polar and equatorial axis: 34 µm and 24 µm, GSC 132110. This grain is tricolporate, with an exine 3 µm thick and a reticulum composed of fused clavae. The reticulum becomes finer toward the colps. The colpal exine is psilate adjacent to the pore, and the pore is rectangular and equatorially elongated. An exinal thickening appears to run in the colpus from the pore to about 2/3 of the way to the pole. C-400773, depth: 1150 m, P4364-98, England Finder Co-ordinate: Q39/3.

Figure 12. *Quercus* sp., polar and equatorial axis: 28 µm and 20 µm, GSC 132111, C-400762, depth: 1040 m, P4364-87, England Finder Co-ordinate: U67.

Figure 13. Rosaceae, polar and equatorial axis: 24 µm and 18 µm, GSC 132112. The protruding pores and faint striate ornament of this grain suggests affinity to Rosaceae (Adams and Morton, 1974, Pl. 24–34). C-400649, depth: 840 m, P4364-66, England Finder Co-ordinate: V47/3.

Figure 14. Rosaceae, polar and equatorial axis: 24 µm and 18 µm, GSC 132113, C-400726, depth: 939.05–939.07 m, P4364-26, England Finder Co-ordinate: V51.

Figure 15. *Shepherdia canadensis*, polar and equatorial axis: 24 µm and 12 µm, GSC 132114. This tricolporate grain has the low verrucate ornament, distinct colpus, and annulated pore of *Shepherdia canadensis* (McAndrews et al., 1973, p. 42; Adams and Morton, 1976, Pl. 45; Bassett et al., 1978, p. 175). C-400592, depth: 113.95–113.97 m, P4364-40, England Finder Co-ordinate: X61.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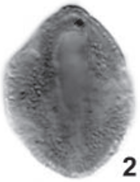
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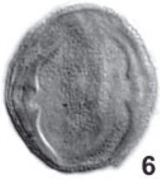
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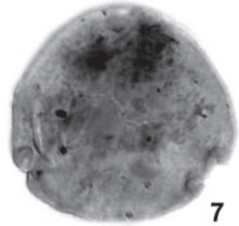
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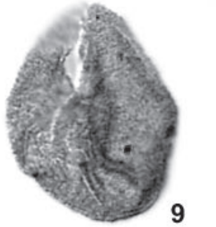
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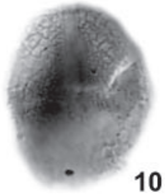
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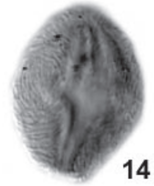
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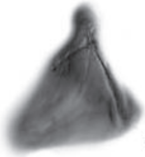
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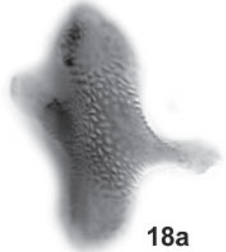
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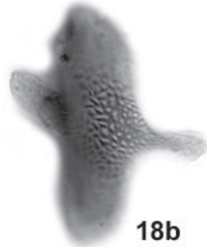
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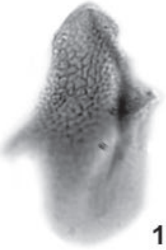
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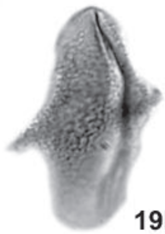
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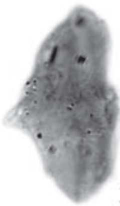
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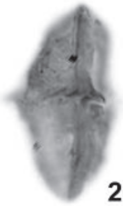
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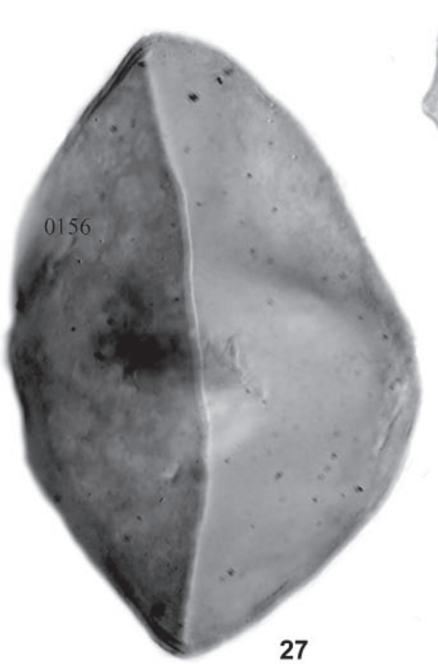

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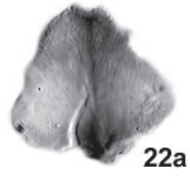
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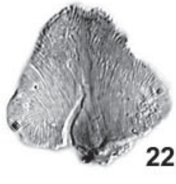
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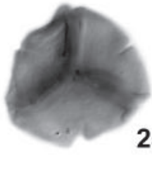
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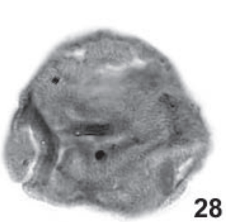
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# Plate 5 (cont.)

Figure 16. *Shepherdia canadensis*, polar and equatorial axis: 34 µm and 16 µm, GSC 132115, C-400762, depth: 1040 m, P4364-87, England Finder Co-ordinate: M54/4.

Figure 17a. (proximal), 17b (amb). *Boehlensipollis hohli* Krutzsch 1972, single longest visible dimension: 20 µm, GSC 132116. This grain shows the features of *Boehlensipollis hohli* Krutzsch 1962 (p. 272, Pl. III, fig. 18–30), i.e. a deep concave amb, thin closed trilete mark (Fig. 17a) extending to the equator where it merges to an atriate pore, and a psilate exine (Fig. 17b). C-400770, depth: 1120 m, P4364-95, England Finder Co-ordinate: O46/2.

Figure 18a. (amb and corpus ornament), 18b (equatorial projection ornament). *Integricorpus* sp. cf. *I. reticulatus* (Mtchedlishvili) Stanley 1970, polar and equatorial axis: 33 µm and 12 µm, GSC 132117. This is a triprojectate grain with an angular microreticulum, becoming distally very fine to scabrate on the projections. Norris' specimens were distally scabate (Norris, 1986, p. 36, Pl. 9, fig. 12–14). The size 34 µm long, 12 µm wide, with 10 µm projections, is within Norris' size range. The projections cannot be accurately measured. *See* the discussion in '*Integricorpus-Parviprojectus* taxonomy' section, herein. C-400739, depth: 946.20–946.22 m, P4364-30, England Finder Co-ordinate: Q40/4.

Figure 19a. (amb and corpus ornament), 19b (equatorial projection). *Integricorpus* sp. cf. *I. reticulatus* (Mtchedlishvili) Stanley 1970, single longest visible dimension: 30 µm, GSC 132118, C-400719, depth: 936.32–936.33 m, P4364-23, England Finder Co-ordinate: P35.

Figure 20a. (equatorial view of amb and equatorial projection), 20b (equatorial view focused on equatorial projection). cf. *Parviprojectus* sp. A of Rouse (1977), polar and equatorial axis: 27 µm and 14 µm, GSC 132119. This specimen is referred to *Parviprojectus* sp. A of Rouse (1977, Pl. 2, fig. 31). Rouse's specimen has polar and equatorial axes of 28 µm and 15 µm with arms about 3 µm long, versus polar and equatorial axes of 27 µm and 14 µm with projections about 3 µm long for this Mallik specimen. The Mallik specimen is crushed and eroded, but has faint, polar-oriented striations as in Rouse's specimen. *See* discussion in '*Integricorpus-Parviprojectus* taxonomy' section, herein. C-400719, depth: 936.32–936.33 m, P4364-23, England Finder Co-ordinate: O36/2.

Figure 21. *Striatocorpus sweetii* sp. nov. (paratype), polar and equatorial axis: 18 µm and 22 µm, GSC 132120. *Striatocorpus sweetii* sp. nov. Crushing obscures the distal pole. *See* Appendix B, herein. C-400755, depth: 990 m, P4364-82, England Finder Co-ordinate: N59.

Figure 22a. (amb and corpus), 22b (the striate ornament on corpus digitally enhanced by an unsharp mask filter). *Striatocorpus sweetii* sp. nov. (holotype), polar and equatorial axis: 20 µm and 22 µm, GSC 132121. This specimen has a striate pattern, normal or slightly oblique to the projections edge, more pronounced at the proximal pole and reducing toward the distal pole, and more pronounced on the outer edge of the projections than toward the body. This specimen may have a slight distal dome, although the distal pole is obscured by a projection. *See* Appendix B, herein. C-400771, depth: 1130 m, P4364-96, England Finder Co-ordinate: S39/3.

Figure 23. *Striatocorpus* sp. cf. *S. sweetii* sp. nov., polar and equatorial axis: 18 µm and 22 µm, GSC 132122. This specimen may represent variation in *S. sweetii*. It is almost isopolar, and nearly rhombic, but the striate ornament is very similar to the holotype and it occurs stratigraphically just 10 m below the holotype. *See* Appendix B, herein. C-400772, depth: 1140 m, P4364-97, England Finder Co-ordinate: V45.

Figure 24. *Gothanipollis*? sp., single longest visible dimension: 20 µm, GSC 132123. This specimen is strongly convex inter-radially, has a distinct trilete mark, and appears to have a germinal apparatus comparable to *Gothanipollis* spp. (Krutzsch, 1959, p. 232–239, Pl. XLVI, XLVII). C-400765, depth: 1070 m, P4364-90, England Finder Co-ordinate: N51/3.

Figure 25. Mallik2L-38 unknown 29, single longest visible dimension: 20 µm, GSC 132124. This specimen is a tetrad, with one slightly protruding colpus visible on each grain. Each colpus appears to have some marginal thickening. The exine is psilate. C-400771, depth: 1130 m, P4364-96, England Finder Co-ordinate: P47/2.

Figure 26. *Magnolia* sp., polar and equatorial axis: 46 µm and 20 µm, GSC 132125. This pollen has the naviculate shape with a sulcus extending to the poles of the grain, and a double wall, but a more reduced ornament compared to that illustrated by Lieux (1980a, Pl. IX–XIII). C-400633, depth: 680 m, P4364-50, England Finder Co-ordinate: H36/2.

Figure 27. *Magnolia* sp., polar and equatorial axis: 84 µm and 54 µm, GSC 132126. The monocolpate structure compares with *Magnolia* spp., as illustrated by Lieux (1980a, Pl. IX–XIII). Modern *Magnolia* pollen ranges from 42–98 µm in longitudinal equatorial axis (Lieux, 1980a). C-400734, depth: 944.31–944.33 m, P4364-28, England Finder Co-ordinate: G44/4.

Figure 28. Mallik2L-38 unknown 16, single longest visible dimension: 26 µm, GSC 132127. This is a subtriangular grain with clavae forming striate ornament. The apertures are difficult to interpret. C-400689, depth: 906.57–906.59 m, P4364-14, England Finder Co-ordinate: T55/1.

Figure 29. Pollen tetrad (scabrate), single longest visible dimension: 34 µm, GSC 132128. This pollen is a planar tetrad with a thin exine and scabrate ornament. It may belong to Ericales. C-400692, depth: 911.99–912.01 m, P4364-15, England Finder Co-ordinate: Q43/3.

Figure 30. *Trudopollis* sp., *T.* ?*barentsii*, single longest visible dimension: 28 µm, GSC 132129. This specimen of *Trudopollis* has a slightly convex amb, has short colpi, and distinctly thickened, psilate exine at the apices. The rest of the grain has scabrate-verrucate exine. It is similar to *T. barentsii* of Spitsbergen (Manum, 1962, p. 49–50, Pl. XII, fig. 24–27) in size and subtriangular outline; however, it has a less coarse ornament, slit-like colps, and no evidence of an inner exinal layer forming a vestibulum. This morphology is similar to *Haloragis* spp., a modern pollen illustrated by Simpson (1960, Pl. XIV, fig. 12–15) and Praglowski (1970, Pl. 7) which is a humid, terrestrial genus mainly represented in the southern hemisphere. C-400772, depth: 1140 m, P4364-97, England Finder Co-ordinate: L63/2.

**Contents**

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