# Palynology, age, and paleoenvironmental interpretations from the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well

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**Abstract:** The JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well was drilled in 1998 to investigate the geological, geochemical, geophysical, and engineering properties of a gas hydrate accumulation previously identified in the Mallik L-38 well. Palynological analysis of core and cuttings from 670 m to 1150 m (TD) are reported here. Detailed quantitative analysis has been done on the 886–952 m cored interval that hosts the main gas hydrate accumulation. The pollen and spore evidence suggests the following biostratigraphic subdivisions for the 670–1150 m succession: 670–785 m, Late Miocene or older; 775–897 m, within the range of Early Miocene to Late Eocene; 897–930 m, probably Late Eocene; 930–995 m, Late Eocene; and 995–1151 m within the range Early to Middle Eocene. Below 930 m the rocks are best assigned to the Richards and upper Taglu sequences. A dominantly continental succession is indicated, with a marginal marine and/or estuarine episode between about 945 m and 948 m, in the Late Eocene. The dinoflagellates in this interval are considered to be indigenous to the sampled rock. There is evidence of two episodes of edaphic–climatic dryness in the Late Eocene and probable Late Eocene.

**Résumé :** Le puits de recherche sur les hydrates de gaz JAPEX/JNOC/GSC Mallik 2L-38 a été foré en 1998 afin d'étudier les propriétés géologiques, géochimiques, géophysiques et techniques d'une accumulation d'hydrates de gaz mise en évidence antérieurement dans le puits Mallik L-38. Les résultats de l'analyse palynologique des carottes et des déblais de forage provenant de l'intervalle de 670 à 1 150 m sont présentés. Une étude quantitative détaillée a été faite de l'intervalle carotté de 886 à 952 m qui contient l'accumulation principale d'hydrates de gaz. Les subdivisions biostratigraphiques suivantes de l'intervalle de 670 à 1 150 m sont fondées sur l'étude des pollens et des spores : de 670 à 785 m, Miocène tardif ou plus ancien; de 775 à 897 m, dans l'intervalle du Miocène précoce à l'Éocène tardif; de 897 à 930 m, probablement Éocène tardif; de 930 à 995 m, Éocène tardif; et de 995 à 1 151 m, dans l'intervalle Éocène précoce–Éocène moyen. Les roches à une profondeur supérieure à 930 m sont attribuées à la séquence de Richards et à la partie supérieure de la séquence de Taglu. La succession aurait une origine surtout continentale, avec un épisode épicontinental ou estuarien à l'Éocène tardif (à environ 945 m et 948 m). Les dinoflagellés de cet intervalle sont considérés comme étant autochtones. Des indications de deux épisodes de sécheresse climatique et édaphique à l'Éocène tardif et à ce qui est probablement l'Éocène tardif ont été observées.

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## INTRODUCTION

The Mallik L-38 gas hydrate research well in the Mackenzie Delta of Arctic Canada (Fig. 1) penetrated an accumulation of gas hydrate (Bily and Dick, 1974). Smith and Judge (1995) have estimated an upper limit of 129–262 Gt of methane stored as gas hydrate in the region. An investigation of the geological, geochemical, geophysical, and engineering properties associated with this gas hydrate accumulation was undertaken by the drilling of the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well (69°27′39″N, 134°39′25″W, total depth (TD) 1150 m) in February–March, 1998 (Dallimore et al., 1999).

Paleontological investigations associated with the Mallik 2L-38 program (McNeil, 1999; Kurita and Uchida, 1999; this report) were conducted to determine the age and



**Figure 1.** *Mallik 2L-38 well and other wells and sections in northwestern North America.*

environment of deposition of the rocks penetrated by the well. Reported here are the distributions of stratigraphically significant pollen and spores from cuttings in the 670–880 m and 960–1150 m intervals, and a relative abundance analysis of pollen and spores in the cored interval from 886–952 m (all depths measured from kelly bushing [8.31 m above sea level]). This last interval hosts gas hydrate (Jenner et al., 1999).

Stratigraphic sequence tops which have been determined for the Mallik L-38 well are Iperk Sequence, 29 ft. (8.8 m), Kugmallit Sequence, 1145 ft. (349 m), and Richards Sequence, 6345 ft. (1934 m) (Dixon, 1990). Sequence tops recognized by Dixon (1990) were based primarily on regional geological correlations, log character, seismic profiles, and to some extent, on paleontology. McNeil and Birchard (1989) indicated the presence of a marine facies of the Richards Sequence in the Mallik L-38 well by the occurrence of *Haplophragmoides richardsensis* McNeil Zone (= *H.* sp. 2000 of McNeil and Birchard, 1989) below 7548 ft. (2300 m).

Based on the interpretation of the Mallik L-38 well, three sequences were identified in the Mallik 2L-38 well: Iperk Sequence, 0–350 m; Mackenzie Bay Sequence, 350–935 m; and Kugmallit Sequence, more than 935 m (Dallimore et al., 1998). Further sedimentology by Jenner et al. (1999) tentatively interpreted the Kugmallit–Mackenzie Bay sequence contact in Mallik 2L-38 well to be at 926.5 m.

McNeil's analysis (1999) of the Foraminifera in the Mallik 2L-38 well indicates that there has been significant recycling of Cretaceous agglutinated foraminifers. He also indicated that the lithology of the section below 670 m is typical of the Oligocene Kugmallit Sequence. The palynomorph evidence presented here shows that, in spite of some recycling, there is a primary biostratigraphic signal in the palynological data which leads to conclusions contradictory to those put forth by Dallimore et al. (1998), Jenner et al. (1999), Kurita and Uchida, (1999), and McNeil (1999).

## METHODS

Paleontological samples from core and cuttings were obtained during drilling operations and core lithological analysis (Dallimore et al., 1999). Thirty-five samples were analyzed from fine-grained, organic-rich beds in the cored interval between 886 m and 952 m. Core samples are referred to here by their depth midpoint although most spanned a 2 cm interval. Forty-two cutting samples were analyzed from 10 m intervals between 670 m and 1150 m (target depth TD), excluding the intervals where core was available. Palynological samples averaging 9–15 g were processed using standard HCl, HF methods and a light cold Javex treatment. Samples were cleaned by ultrasonic screening with screens of 150 µm and 7 µm nominal openings, yielding a fraction for analysis between about 210 µm and 10 µm. For all samples palynomorphs were identified and counted. In the cored interval palynomorph sums range from 63–316 specimens, depending on the abundance of palynomorphs on the slide. In the
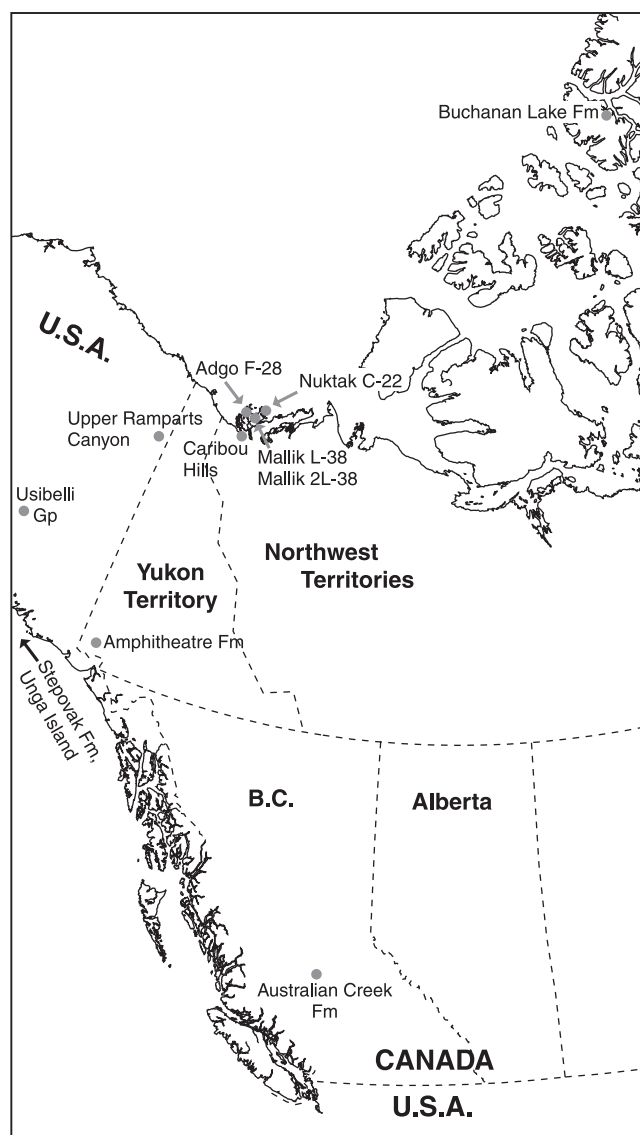
cored interval, percentages of palynomorphs have been calculated on the total count sum of palynomorphs in a sample (including recycled palynomorphs), in order to determine the dominant changes in assemblage though the core interval. For this paper, data from the cutting intervals are presented only as records of biostratigraphically significant taxa.

Recycled spores occur in most samples. Most recycled palynomorphs could not be discretely identified but preservational features and/or diagenetic colour attributes allowed assignment to the unidentified 'recycled palynomorph' category.

## RESULTS AND INTERPRETATION

Figure 2 shows the distribution of biostratigraphically significant taxa in the 670–1150 m interval, including taxa in the 886–952 m cored interval. These data are presented by last appearance datums (LAD) because much of the data are from cuttings. Although the caliper log does not exhibit much caving below the casing (Dallimore et al., 1999) there has been some enlargement of the well bore and consequent caving of palynomorphs in the cuttings, but caving is excluded from affecting the results of core samples. In the upper 670 m of the well, only the short cored intervals above 175 m were analyzed (not reported here). Thus, one can not be sure that taxa do not occur above the LAD shown here, although any putative higher occurrences would generally have a large gap between their lower and upper stratigraphic occurrences. A testament to the quality of the cutting data is found in the fossil impoverishment of several cutting samples, which indicates that cuttings were not contaminated by a 'palynomorph soup' circulating in the drilling mud, causing abundant spurious occurrences of palynomorphs. Variations in concentration and composition of assemblages, seen during analysis, showed that the palynomorph signal was primarily responding to assemblage changes in the penetrated rocks.

Table 1 gives literature references for the age interpretations made for taxa reported in Figure 2, and gives the formation or sequence stratigraphic association of these taxa. Much of the comparative data has been derived from the Adgo F-28 well where Norris (1997) presented his latest palynostratigraphic zonation for the Cenozoic series in the Mackenzie–Beaufort Basin, founded on previous work in the Nuktak C-22 well (Norris, 1986). Norris' taxonomy has been followed for taxa which are not certainly referable to modern families, genera, and species. It is to be noted that caving in the industrial Adgo F-28 well has probably caused some spurious downward range extension of palynomorphs. Table 1 also cites the occurrence of significant palynomorphs at selected high-latitude sections in Canada and Alaska. One lower latitude section, the Australian Creek Formation in British Columbia is also cited, as it is a key formation for Late Eocene assemblages. The citation of the occurrences of biostratigraphically significant taxa is not intended as an exhaustive review, but is illustrative of the high-latitude stratigraphic ranges of these taxa.

The percentage pollen diagram has been broken into three figures for ease of presentation. Figure 3 presents the relative abundance of recycled palynomorphs, algae, fungi, and *Sphagnum*. Figure 4 presents the relative abundance of ferns and allies and gymnosperms. Figure 5 presents the relative abundance of angiosperm pollen. Figures 3–5 show variability but no dominant trends in percentages of pollen and spores.

Recycled palynomorphs are present in most samples (Fig. 3). Amongst the discretely identifiable recycled taxa is the Carboniferous *Densosporites rarispinosus* Playford 1963 (937.36 m). *Aquilapollenites quadrilobus* Rouse 1957 (946.21 m and 951.29 m) and *Aquilapollenites magnus* (Mchedlishvili) Rouse and Srivastava 1972 (946.2 m) have Campanian–Maastrichtian age ranges (Tschudy and Leopold, 1970; Rouse and Srivastava, 1972). Many other taxa which occur sporadically have generalized Mesozoic age ranges, viz., *Classopollis classoides* (Pflug) Pocock and Jansonius 1961; *Vitreisporites pallidus* (Reisinger) Nilsson 1958; or a Cretaceous age range, viz., *Cicatricosisporites australiensis* (Cookson) Potonié 1956 (Singh, 1971).

### *Age interpretation*

#### 670 m to 775 m, Late Miocene or older

There are few age indicators in this interval, but the presence of *Diervilla echinata* indicates an age older than Late Miocene (Leopold and Liu, 1994; White et al., in press). No assemblage rich in thermophilous taxa typical of the Middle Miocene (White and Ager, 1994; White et al., 1997) was encountered, and it is expected that rocks of that age, if present in the well, are hidden in the cased interval above 670 m.

#### 775 m to 897 m, Early Miocene–Late Eocene

*Castanea*-type and *Liquidambar* pollen occur in this interval. They are present in the Middle Miocene, Upper Ramparts Canyon section (White and Ager, 1994), and range downward of the Middle Miocene at high latitude. *Jussiaea (Ludwigia)* was first recorded in the Late Eocene (Piel, 1971; Long and Sweet, 1994), and although younger records are not available, its affinity with modern *Ludwigia* suggests that it ranges into younger rocks. Thus, its presence is not considered to necessarily indicate a Late Eocene age. Similarly, *Verrucatosporites favus* also suggests a Late Eocene age, but this biostratigrahic limit is here not considered to be definitive. Thus, this interval is constrained between the Early Miocene and the Late Eocene.

#### 897 m to 930 m, probable Late Eocene

*Lonicerapollis gallwitzii* and *Hypoxylonites* sp. appear in the 897.36 m core sample. In the Adgo F-28 well, the LAD of *L. gallwitzii* is at 2300 ft. (701 m), in the lowest Mackenzie Bay Sequence, and *H. pirozynskioides* is at 2700 ft. (823 m), in the uppermost Richards Sequence. In the Adgo F-28 well there is interpreted to be a significant erosional hiatus during Oligocene time between the Richards and Mackenzie Bay

| depth (m) | Taxon | Diervilla echinata Piel 1971 | Ilex -type | Castanea -type | Jussiaeae (Ludwigia) sp. | Pinus koraiensis-type | Verrucatosporites favus (Potonié) Thompson and Pflug 1953 | Liquidambar sp. | Tilia -type | Paraalnipollenites alterniporus (Simpson) Srivistava 1975 | Hypoxylonites sp. | Loniceripollis gallwitzii Krutzsch 1962 | Desmidiospora sp. | Integricorpus sp. A of Norris (1986) | Parviprojectus sp. A of Ridgway et al. (1995) | Boisduvalia clavatites Piel 1971 | Aceripollenites tener (Samoilovitch) Norris 1997 | Rhoipites cf. microreticulatus of Norris (1997) | Mancicorpus sp.of Ridgway et al. (1995) | Cicatricosisporites paradorogensis Krutzsch 1959 | Pistillipollenites mcgregorii Rouse 1962 | Foveosporites sp. | Parviprojectus sp. (intermediate form) | Platycarya sp. | Striadiporites inflexus (Ke et Shi ex Sung et al.) Norris 1986 | Psilastephanocolpites cf. marginatus of Norris (1997) | Juglanspollenites verus sensu Norris (1997) | Engelhardtia/Alfaroa | Foveosporites sp. of Norris (1997) | Rhoipites sp. of Norris (1997) | age |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 670 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ↑casing |
| 680 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 690 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 700 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Late Miocene or older |
| 710 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 720 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 730 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 740 | CU | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 750 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 760 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 770 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 775 m |
| 780 | CU | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 785 | CU | | | 1 | 1 | 2 | 2 | | | | | | | | | | | | | | | | | | | | | | | | |
| 800 | CU | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | |
| 810 | CU | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 820 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Early Miocene– Late Eocene |
| 830 | CU | | | | 1 | | | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| 840 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 850 | CU | | | | 1 | | | | 1 | | | | | | | | | | | | | | | | | | | | | | |
| 860 | CU | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | |
| 870 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 880 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 886.38 | CO | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 890.71 | CO | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | |
| 891.08 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 892.51 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 893.18 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 896.71 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 897 m |
| 897.36 | CO | | | | | | | | | | | | | 2 | 1 | | | | | | | | | | | | | | | | |
| 900.44 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 900.63 | CO | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 903.01 | CO | | | | | | | | | | | | | 2 | 1 | | | | | | | | | | | | | | | | Probable Late Eocene |
| 903.35 | CO | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | |
| 903.82 | CO | | | | 1 | | | | | | | | | 1 | | | | | | | | | | | | | | | | | |
| 905.74 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 906.58 | CO | | | | 1 | 1 | | | | | | | | 2 | | | | | | | | | | | | | | | | | |
| 912.00 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 920.31 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 921.39 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 925.58 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 925.70 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 928.01 | CO | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 928.81 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 930 m |
| 935.78 | CO | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | |
| 936.32 | CO | | | | | | | | | | | | | | | | 1 | 1 | | | | | | | | | | | | | |
| 936.76 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 937.36 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 939.06 | CO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 943.73 | CO | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | Late Eocene |
| 944.32 | CO | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | |
| 945.21 | CO | | | | | | | | | | | | | | | | | | | 1 | 1 | | | | | | | | | | |
| 946.21 | CO | | | | | | | | | | | | | | | | | 1 | | | 1 | | | | | | | | | | |
| 947.61 | CO | | | | | | | ? | | | | | | | | | | | | | | | | | | | | | | | |
| 948.16 | CO | | | | | | | | | | | | | | 1 | | | | | | 1 | | | | | | | | | | |
| 949.21 | CO | | | 1 | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | |
| 950.11 | CO | | | | | | | | | | | | | | 2 | | | | 1 | | 1 | | | | | | | | | | |
| 951.29 | CO | | | | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | |
| 960 | CU | | | | | | | | | | | | | | | 1 | | | | | | | 1 | | | | | | | | |
| 970 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 980 | CU | | | | | | | | | | | | | 1 | 2 | | | | | | | | | | | | | | | | |
| 990 | CU | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | 995 m |
| 1000 | CU | | | | | 1 | 1 | | | | | | | | | | | | | | 1 | 3 | 2 | | | | | | | | |
| 1010 | CU | | | | | | | | | | | | | | | | | | | | 1 | | | 1 | | | | | | | |
| 1020 | CU | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1030 | CU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1040 | CU | | | | | | | | 1 | | | | | | | | | | | | | 1 | 1 | | 1 | 1 | | | | | Early to Middle Eocene |
| 1050 | CU | | | | | | | ? | | | | | | | | | | | | | 1 | | | | | | 1 | | | | |
| 1060 | CU | | | | | 1 | | | | | | | | | | | | | | | | | | | | | 1 | 1 | | | |
| 1070 | CU | | | 1 | | 1 | | 1 | | | | | | | | | | | | | | | | | | | | 1 | | | |
| 1080 | CU | | | | | 1 | | | | | | | | | | | | | | | 1 | | 1 | | | | | | | | |
| 1090 | CU | | | | | | | | | | | | | | | | | | | | | 1 | | 2 | | | | | | | |
| 1100 | CU | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | 1 | | | |
| 1110 | CU | | | | | | | | 1 | | 3 | | | | | | | | | | 1 | | | | | | | | 1 | | |
| 1120 | CU | | | | | | | | | | 1 | | | | | | | | | | 1 | | | | | | | | | ? | |
| 1130 | CU | | | | | | | | 1 | | 1 | | | | | | | | 2 | | | | | | | | | | 1 | | |
| 1140 | CU | | | 1 | | | | | | | | | | | | | | | 1 | | | | | | | | 1 | | 1 | | |
| 1150 | CU | | | | | | 1 | 1 | | | 1 | | | | | | | | | | | | | | | | | | | 1 | TD |

CO = Core   CU = Cutting

***Figure 2.*** *Count of biostratigraphically significant pollen and spores in the 670–1150 m succession of the Mallik 2L-38 well.*

**Table 1.** Biostratigraphically significant taxa in the Mallik 2L-38 well, 670 m to 1150 m. Typical age ranges, formation or sequence affiliations, and references.

| Taxon | Age range | Formation or sequence affiliation | Reference |
|---|---|---|---|
| *Diervilla echinata* | Late Eocene<br><br>Late Miocene | Australian Creek Fm.; lower Cement Creek sect., Amphitheatre Fm.<br>Usibelli Group | Piel, 1971, p.1916; Ridgway et al., 1995<br><br>Leopold and Liu, 1994; White et al., in press |
| *Ilex* -type | Middle Eocene<br>Middle Miocene | Buchanan Lake Fm.<br>Usibelli Group | McIntyre, 1991<br>Leopold and Liu, 1994; White et al., in press |
| *Castanea* -type | Middle Eocene<br>Middle Miocene | Buchanan Lake Fm.<br>Usibelli Group | McIntyre, 1991<br>Leopold and Liu, 1994; White et al., in press |
| *Jussiaea (Ludwigia)* sp. | Late Eocene<br>Late Eocene | Australian Creek Fm.<br>Amphitheatre Fm., Burwash Basin | Piel, 1971; Long and Sweet, 1994<br>Ridgway et al., 1995 |
| *Pinus koraiensis*-type | Middle Miocene and ?older | Upper Ramparts Canyon | White and Ager, 1994 |
| *Verrucatosporites favus* (Potoniéé) Thompson and Pflug 1953 | Early Eocene to Late Eocene | upper Taglu to Richards seq. (2800–5400 ft) | Norris, 1997, Fig. 3 |
| *Liquidambar* sp. | Eocene to Late Eocene<br>Middle Miocene | Amphitheatre Fm., Burwash Basin<br>Upper Ramparts Canyon sedimentary rocks | Ridgway et al., 1995<br>White and Ager, 1994 |
| *Tilia* -type | Early Eocene<br>Late Miocene | <br>Usibelli Group | Rouse, 1977<br>Leopold and Liu, 1994; White et al., in press |
| *Hypoxylonites* sp. | Late Paleocene to Late Eocene | Aklak, Taglu and Richards seq. (2700–9900 ft) | Norris, 1997, Fig. 3 |
| *Lonicerapollis gallwitzii* Krutzsch 1962 | Late Eocene to Miocene | upper Richards to lower Mackenzie Bay seq. (2300–2900 ft) | Norris, 1997, p. 43 |
| *Desmidiospora* sp. | Paloecene-Early Eocene | middle and upper Taglu seq. (4400–7900 ft) | Norris, 1997, p. 36 |
| *Integricorpus* sp. A of Norris (1986) | Early Eocene-Late Eocene | upper Taglu and Richards seq. (2800–5400 ft) | Norris, 1997, Fig. 3 |
| *Parviprojectus* sp. A  of Ridgeway et al. (1995) | Early Oligocene | upper Cement Creek sect., Amphitheatre Fm. | Ridgway et al., 1995 |
| *Boisduvalia clavatites* Piel 1971 | Late Eocene<br>Late Eocene | Australian Creek Fm.<br>lower Cement Creek sect., Amphitheatre Fm. | Piel, 1971; Long and Sweet, 1994<br>Ridgway et al., 1995 |
| *Aceripollenites tener* (Samoilovitch) Norris 1997 | Early to Late Eocene | upper Taglu and Richards seq. (2800–4100 ft) | Norris, 1997, p. 38 |
| *Rhoipites* cf. *microreticulatus* of Norris (1997) | Early Eocene | upper Taglu Seq. (4600–5100 ft) | Norris, 1997,  p. 41 |
| *Paraalnipollenites alterniporus* (Simpson) Srivastava 1975 | Paleocene<br><br>Eocene | <br><br>Caribou Hills | Rouse, 1977<br><br>Ioannides and McIntyre, 1980 |
| *Mancicorpus* sp. of Ridgway et al. (1995) | Late Eocene<br><br>Early Oligocene | middle Cement Creek sect., Amphitheatre Fm.<br>Stepovak Fm. | Ridgway et al., 1995<br><br>Marincovich and Wiggins, 1990; V.D. Wiggins, unpub. data, 1988 |
| *Cicatricosisporites paradorogensis* Krutzsch 1959 | Middle Eocene to middle Oligocene | | Krutzsch, 1967, p. 80 |
| *Pistillipollenites mcgregorii* Rouse 1962 | Late Paleocene to Middle Eocene<br><br>Late Paleocene to Middle Eocene | Aklak–Taglu seq. (3500–10 530 ft) | Norris, 1997, Fig. 3<br><br>Rouse, 1977 |
| *Parviprojectus* sp. | intermediate form between Paleocene *P. striatus*  and Oligocene *Parviprojectus* | | A.R. Sweet, pers. comm., 1999 |
| *Striadiporites inflexus* (Ke et Shi ex Sung et al.) Norris 1986 | Paleocene to Early Eocene | middle and upper Taglu Seq. (4800–7700 ft) in F-28; Richards Seq., (9000–10 400 ft in C-22) | Norris, 1997, Fig. 3; Norris, 1986, Fig. 7 |
| *Psilastephanocolpites* cf. *marginatus*  of Norris (1997) | Middle Eocene | uppermost Taglu  Seq. (3600–3700 ft) | Norris, 1997, Fig. 3 |
| *Juglanspollenites verus* sensu Norris (1997) | Early to Late Eocene | upper Taglu and Richards seq. (2700–4800 ft) | Norris, 1997, p. 48 |
| *Engelhardtia/Alfaroa* | Middle Eocene (and younger) | Buchanan Lake Fm. | McIntyre, 1991 |
| *Momipites coryloides* Wodehouse 1933 | Eocene | | Rouse, 1977 |
| *Foveosporites* sp. of Norris (1997) | Early Eocene | upper Taglu Seq. (5100–5400 ft) | Norris, 1997, p. 38 |
| *Rhoipites* sp. of Norris (1997) | Early to Middle Eocene | uppermost Taglu Seq., Adgo F-28 (3700–4400 ft.) | Norris, 1997, p. 41 |

sequences. This implies that *L. gallwitzii* ranges through the Oligocene, whereas the *Hypoxylonites* suggests an age in the Late Eocene. Thus, indicator taxa allow a Late Eocene or possible Oligocene age for the 897–930 m interval. However, the palynological relative abundance diagrams provide further information for age inferences. A change in palynological assemblage from warm temperate to cool temperate and from angiosperm to gymnosperm dominance has been documented across the Eocene–Oligocene transition in the Amphitheatre Formation, Burwash Basin (Ridgway et al., 1995). The per cent pollen diagrams (Fig. 3, 4, 5) show no such transition between this interval and the underlying Late Eocene rocks; they are virtually indistinguishable in relative abundance composition. Thus, this unit is interpreted to be of probable Late Eocene age.

## 930 m to 995 m, Late Eocene

In the core interval between 930 m and 952 m there are three occurrences of *Integricorpus* sp. A of Norris 1986, which is the nominate species of the *Integricorpus* Zone, of Late Eocene age (Norris, 1997). *Aceripollenites tener* (Samoilovitch) Norris 1997 also occurs within this 930 to 952 m core interval; *A. tener* also has a LAD within the *Integricorpus* Zone in Adgo F-28. Norris (1997) interprets the *Integricorpus* Zone to be Late Eocene. In the Mallik 2L-38 well, two other indicator taxa support this age interpretation. *Boisduvalia clavatites* Piel 1971 is found in the Late Eocene Australian Creek Formation of British Columbia (Piel, 1971; Long and Sweet, 1994) and the Late Eocene portion of the
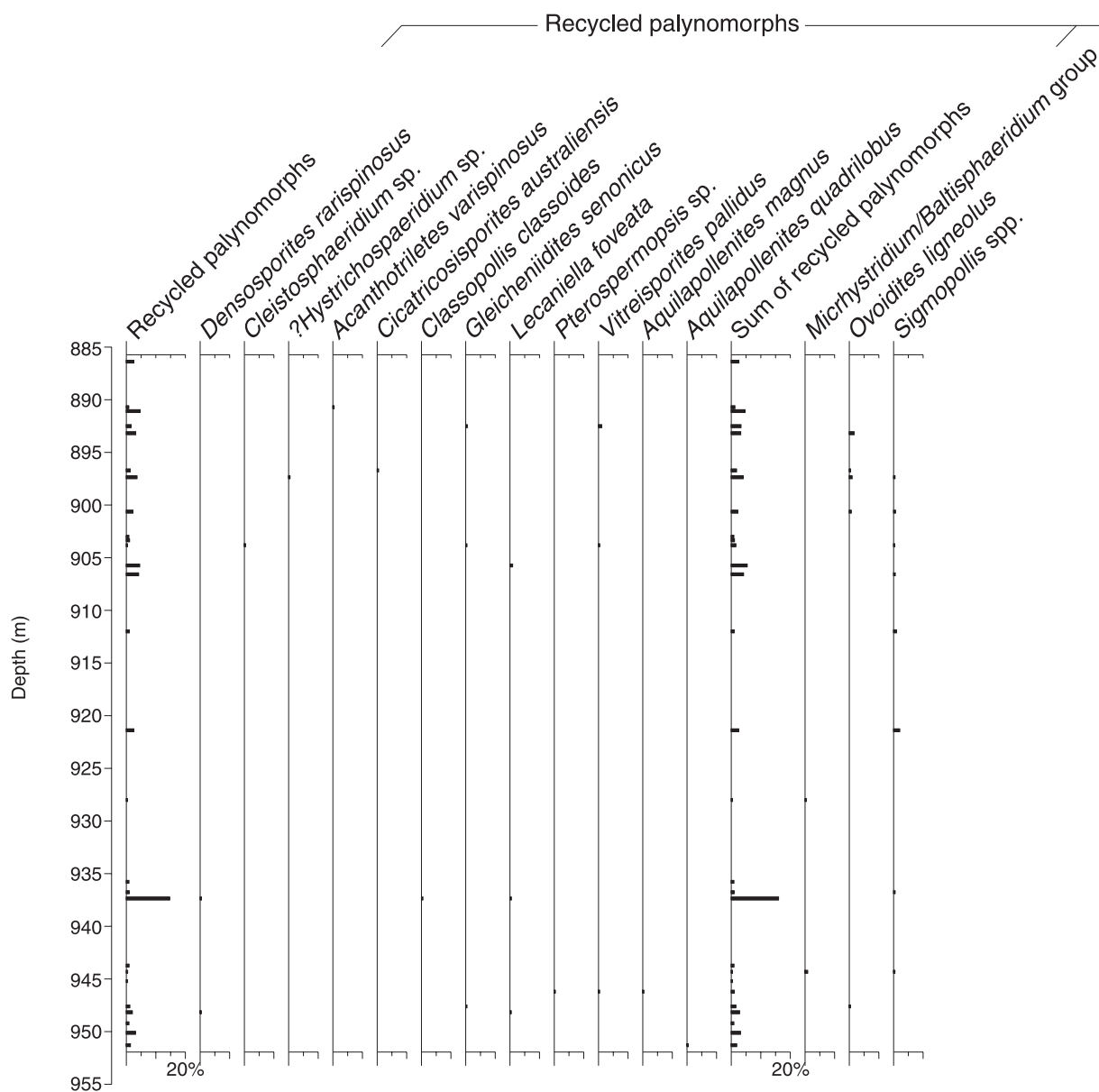


**Figure 3.** *Percentage composition of recycled palynomorphs, algae, fungi and Sphagnum in the 886–952 m cored interval.*

Amphitheatre Formation, Yukon Territory (Ridgway et al., 1995). *Boisduvalia clavatites* does not occur in the Adgo F-28 well or Nuktak C-22 well (Norris, 1986, 1997). *Mancicorpus* sp. of Ridgway et al. (1995) occurs in the cuttings at 990 m in the 2L-38 well. *Mancicorpus* sp. is also found in the Late Eocene of the Amphitheatre Formation (Ridgway et al., 1995), and also in the Early Oligocene of the Stepovak Formation, Unga Island (Marincovich and Wiggins, 1990; V.D. Wiggins, unpub. data, 1988).

Kurita and Uchida (1999) reported dinoflagellate cysts from core samples at 945.21 m and 948.16 m. The stratigraphic ranges of these dinoflagellates fall within the Paleocene–Eocene. This dinoflagellate evidence is consistent with the pollen and spore age range, though the latter indicates a Late Eocene age.

The upper limit of this interval at 930 m is drawn on biostratigraphic grounds, but is nearly coincident with Jenner et al.'s (1999) proposed Mackenzie Bay–Kugmallit contact at 926.5 m, although these data do not support their sequence interpretation.

### 995 m to 1150 m, Early to Middle Eocene

*Pistillipollenties mcgregorii* Rouse 1962, one of the most important biostratigraphic markers in the Paleogene, occurs in cuttings at 1000 m. *Pistillipollenties mcgregorii* is of Early to Middle Eocene age (Rouse, 1977). The 1000 m sample also contains *Cicatricosisporites paradorogensis* Krutzsch 1959, of Middle Eocene to middle Oligocene age in Europe (Krutzsch, 1967). The coincidence of these two taxa suggests
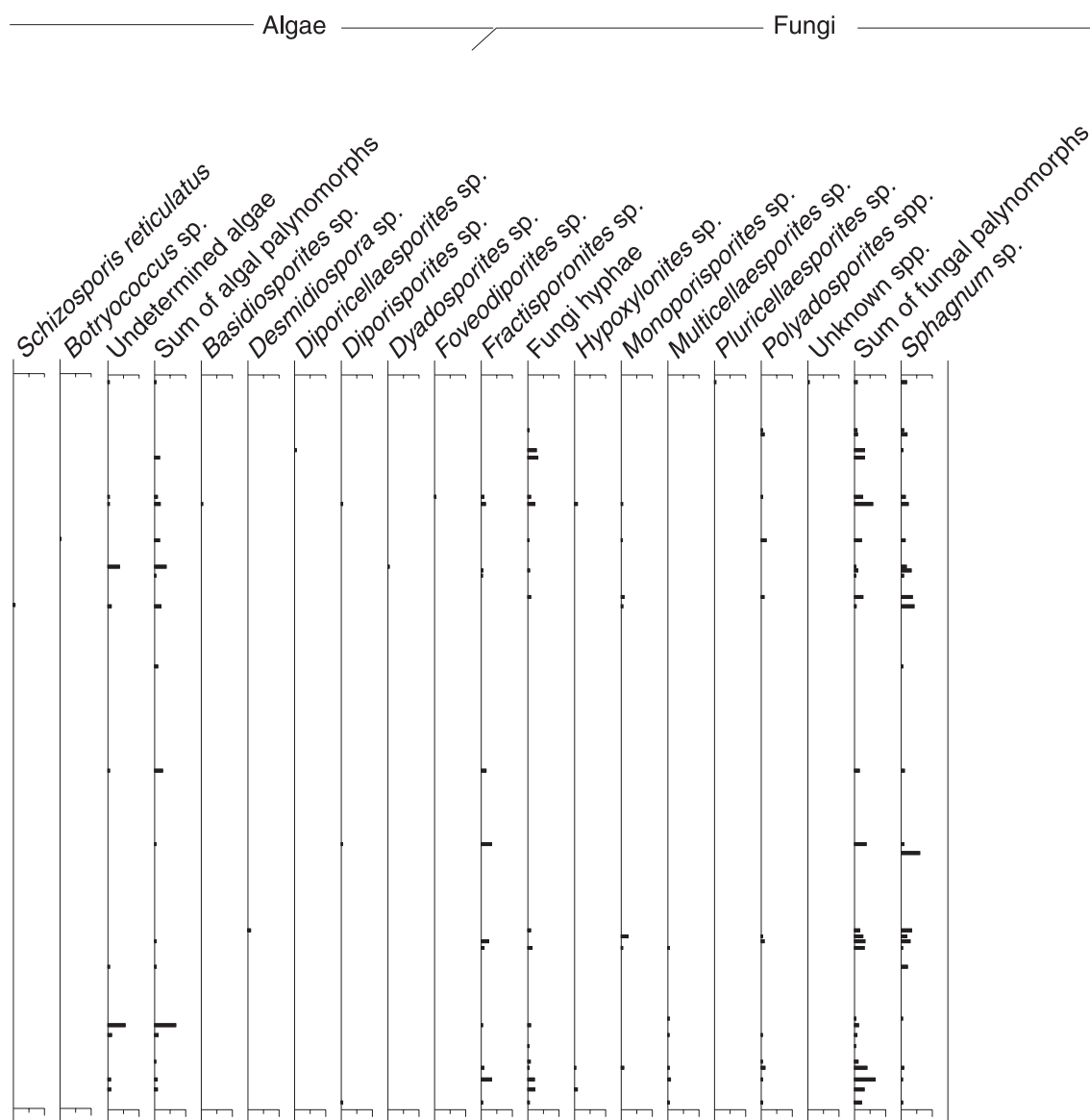


*Figure 3* (cont.)

an age in the Middle Eocene, although *C. paradorogensis* has apparently not been reported previously from Canada, and its northern Canadian range is uncertain.

In the interval between 1050 m and 1150 m occur several taxa also found in the Adgo F-28 well (Norris, 1997) which are associated with a Middle Eocene age (*Psilastephanocolpites* cf. *marginatus* of Norris 1997), an Early to Middle Eocene age (*Rhoipites* sp. of Norris 1997), an Early Eocene age (*Foveosporites* sp. of Norris 1997), and a Paleocene to Early Eocene age (*Striadiporites inflexus* (Ke et Shi ex Sung et al.) Norris 1986).

An Early to Middle Eocene age is indicated for the 995–1150 m interval of the Mallik 2L-38 well.

## Sequence affiliation

The age determinations (above) and a comparison of the distributions of taxa (Table 1) implies that the sediments below 930 m in the Mallik 2L-38 well are referable to the Richards and upper Taglu sequences, as those sequences are identified in the Adgo F-28 well. The sequence affinity of the sediments above 930 m is less certain.

## Paleoenvironment

In his discussion of the Adgo F-28 well, Norris (1997) noted that the *Integricorpus* zone contains a sparse dinoflagellate flora suggestive of a restricted marine or low-salinity environment. The dinoflagellate assemblage recovered from the
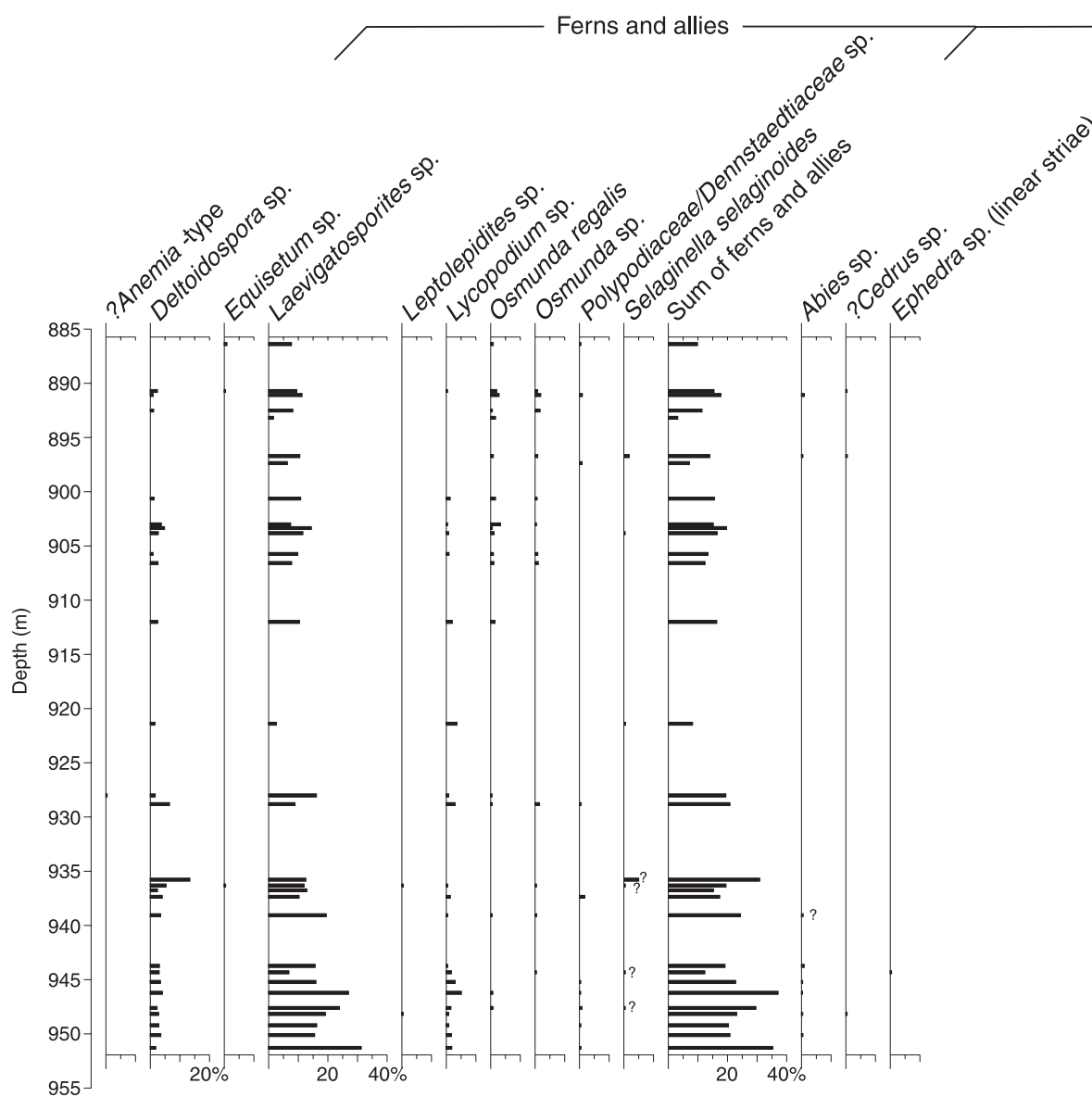


**Figure 4.** *Percentage composition of Ferns and Allies and Gymnosperms in the 886–952 m cored interval.*

Mallik 2L-38 well at 945.21 m and 948.16 m (Kurita and Uchida, 1999) shows impoverishment similar to the Adgo F-28 well. Although the 1150–670 m succession is dominantly continental, the dinoflagellates at 948 m and 945 m suggest a brief episode of nearshore, brackish environment. A distal floodplain-estuarine environment could be consistent with bioturbation and the occurrence of lignites in the core interval below 926 m (Jenner et al., 1999).

### Percentage composition of the core interval

The algae in the 886–952 m core interval include one occurrence of *Botryococcus* (Fig. 3), which is consistent with a fresh to brackish environment. Fungi are common in palynological assemblages in the Eocene. Gymnosperms (Fig. 4) dominate the pollen and spore assemblages, the most common taxa being *Picea* spp., *Pinus* spp., and Taxodiaceae-Cupressaceae-Taxaceae. Ferns and allies are common elements of the assemblage. Angiosperms are the second most dominant group in the palynological assemblage. *Alnus* spp., Ericales, and betulaceous pollen are the most common angiosperms (Fig. 5). The percentage pollen diagrams show no strong trends of change in composition throughout the cored interval 886–952 m.

### Paleoclimatology

Thermophilic hardwoods including *Carya*, *Pterocarya*, *Ulmus*-type, *Castanea*-type, and *Tilia*-type are suggestive of modern, mid-latitude climatic conditions. In addition,
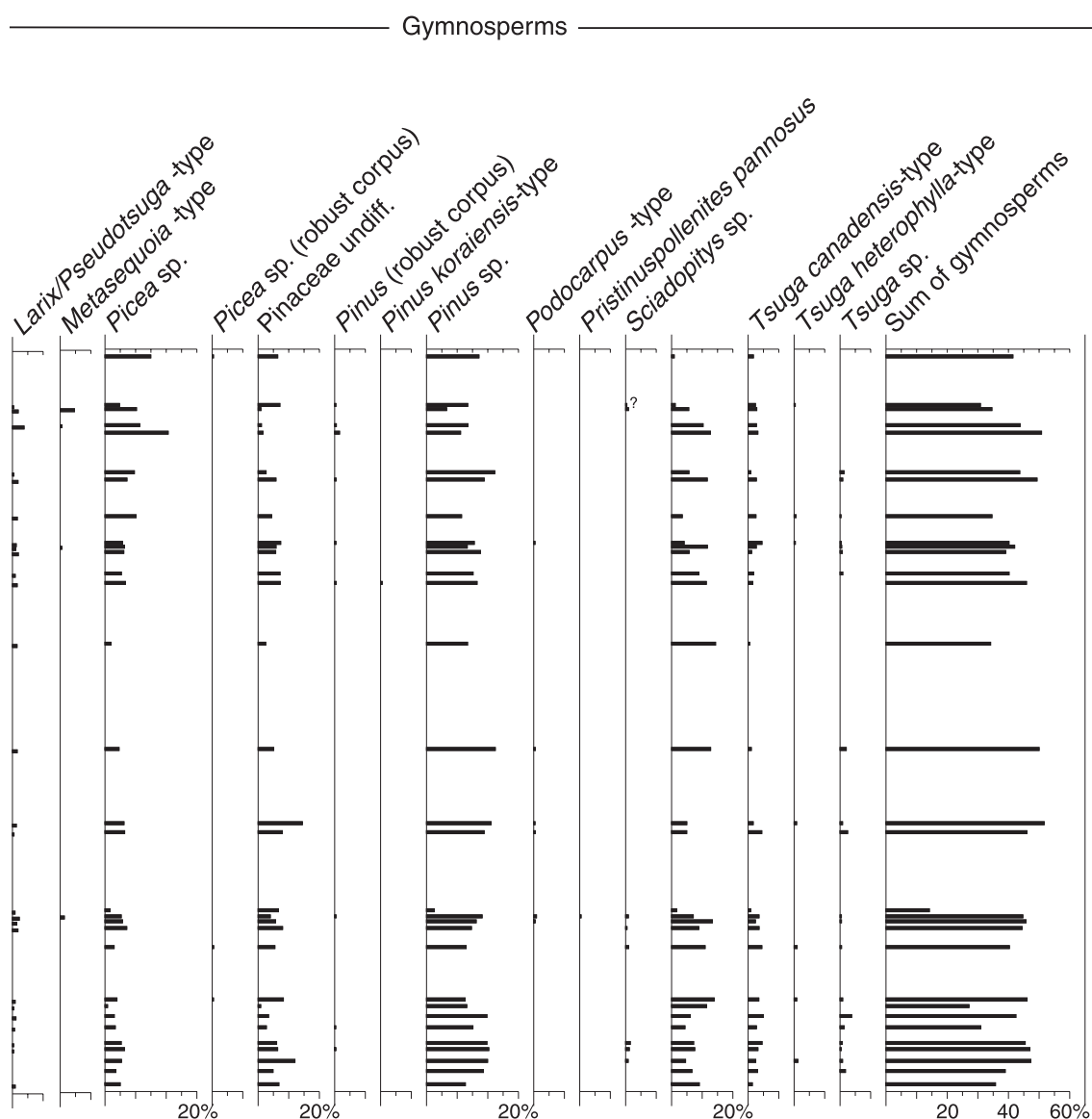


**Figure 4** *(cont.)*

the autecology of modern gymnosperms related to the Eocene genera suggests the presence of drying episodes during the Late Eocene.

Both *Pinus* and *Picea* gymnosperm genera are widely distributed in the Northern hemisphere, and show a wide range of climatic tolerances. However, their modern distributions suggest that *Pinus* spp. are generally more tolerant of warm climates than *Picea* spp. (Hora, 1981, p. 67, 70). Everett (1969, p. 48) noted "As a Group, the pines favour open, wind-swept, 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." Thus, a ratio of the abundant pollen taxa, *Pinus* spp. and *Picea* spp., will at least partially reflect a warm-dry (*Pinus* spp.) to cool-moist (*Picea* spp.) climatic gradient.

The genus *Tsuga* is distributed in temperate to warm, moist environments (Hora, 1981, p. 74). *Tsuga* spp. "...do not thrive in dry soils." (Everett, 1969, p. 64).

*Ephedra* grows in the southwestern United States and in arid regions of South America and the Old World (Kapp, 1969, p. 39). However, Frederiksen (1985) notes *Ephedra* as an example of a genus that may have had broader ecological tolerance in the Late Cretaceous and Early Tertiary than it does at present. It is commonly reported in the lower Tertiary, from brackish to marine deposits, perhaps indicating that it grew on edaphically dry sand dunes, and was perhaps halophytic as well as xerophytic.

Figure 6 shows the *Pinus/Picea* ratio, and the relative abundance of *Tsuga* spp. copied from Figure 2. The most notable event is at 944.32 m, where a high *Pinus/ Picea* ratio
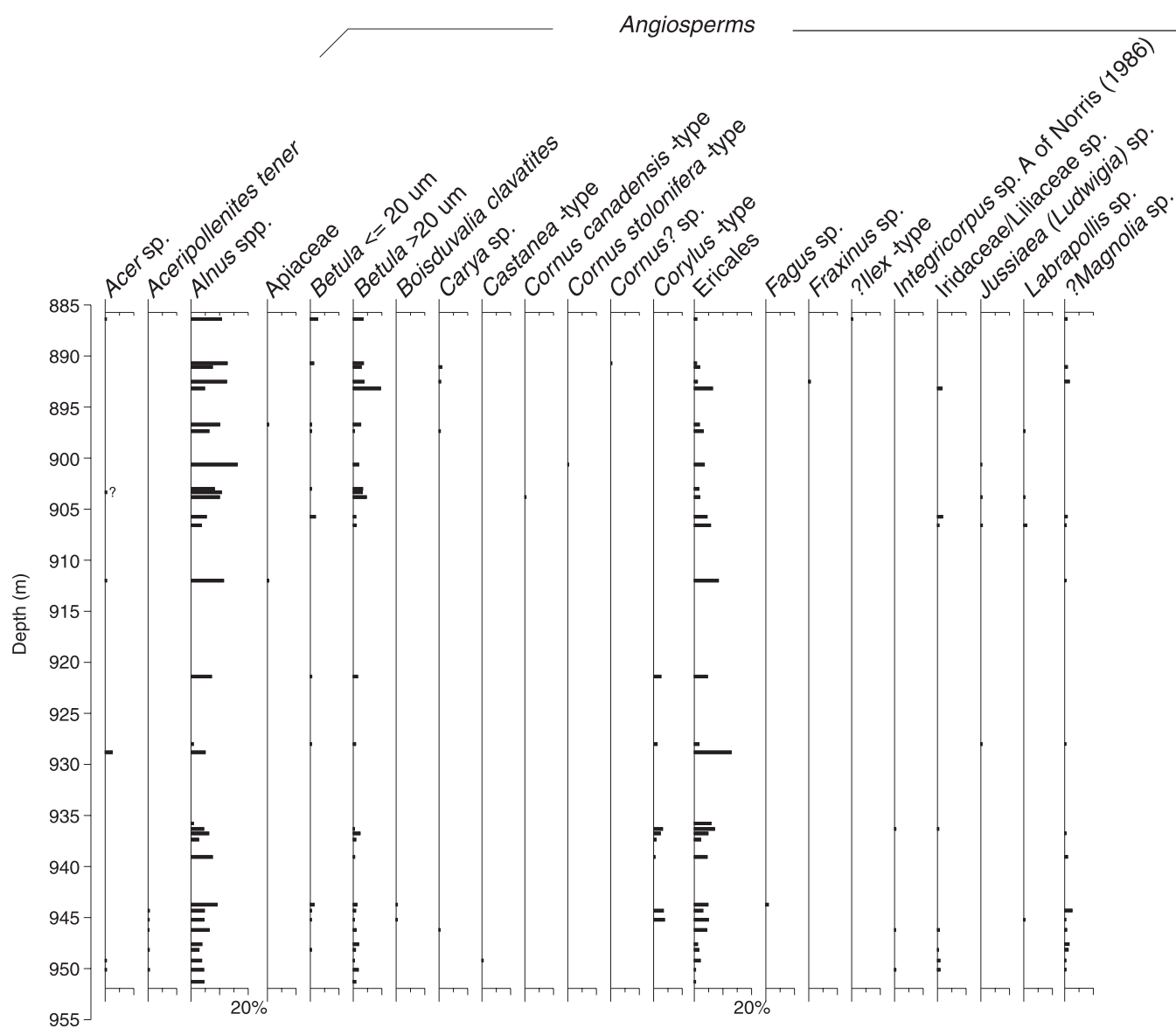


**Figure 5.** *Percentage composition of Angiosperms in the 886–952 m cored interval.*

occurs, an abrupt change from adjacent samples. This is coincident with events unique amongst the samples — the absence of *Tsuga* spp. and the occurrence of *Ephedra* pollen. Thus, several lines of evidence point towards the interpretation that this event represents an edaphic and/or climatic dry cycle. The proximity to the occurrence of dinoflagellates suggests that edaphic conditions were significant, as suggested by Frederiksen (1985). The second most prominent peak in the *Pinus/Picea* ratio is at 912.00 m, also coincident with a very low *Tsuga* percentage. In this case, the events are possibly indicative of the same type of climatic and/or edaphic drying event, but are culminations of longer trends. Nonetheless, there are low *Tsuga* percentage events which do not coincide with *Pinus/Picea* ratio peaks, such as at 933.32 m; the significance of these is unknown. Thus, the evidence is interpreted

to indicate one and perhaps two edaphic and/or climatic drying events within the Late Eocene and probable Late Eocene record.

## SUMMARY

Indicator taxa from the Mallik L-38 well show a succession in ages from TD (1150 m) to the base of casing (670 m) of 'Early to Middle Eocene', 'Late Eocene', 'probable Late Eocene', 'Early Miocene to Late Eocene', and 'older than Late Miocene'. This stratigraphic and chronological succession demonstrates that the palynomorph assemblages are not a random collection of taxa recycled from older rocks. Moreover, the Late Eocene age interpretation is consistent with, but
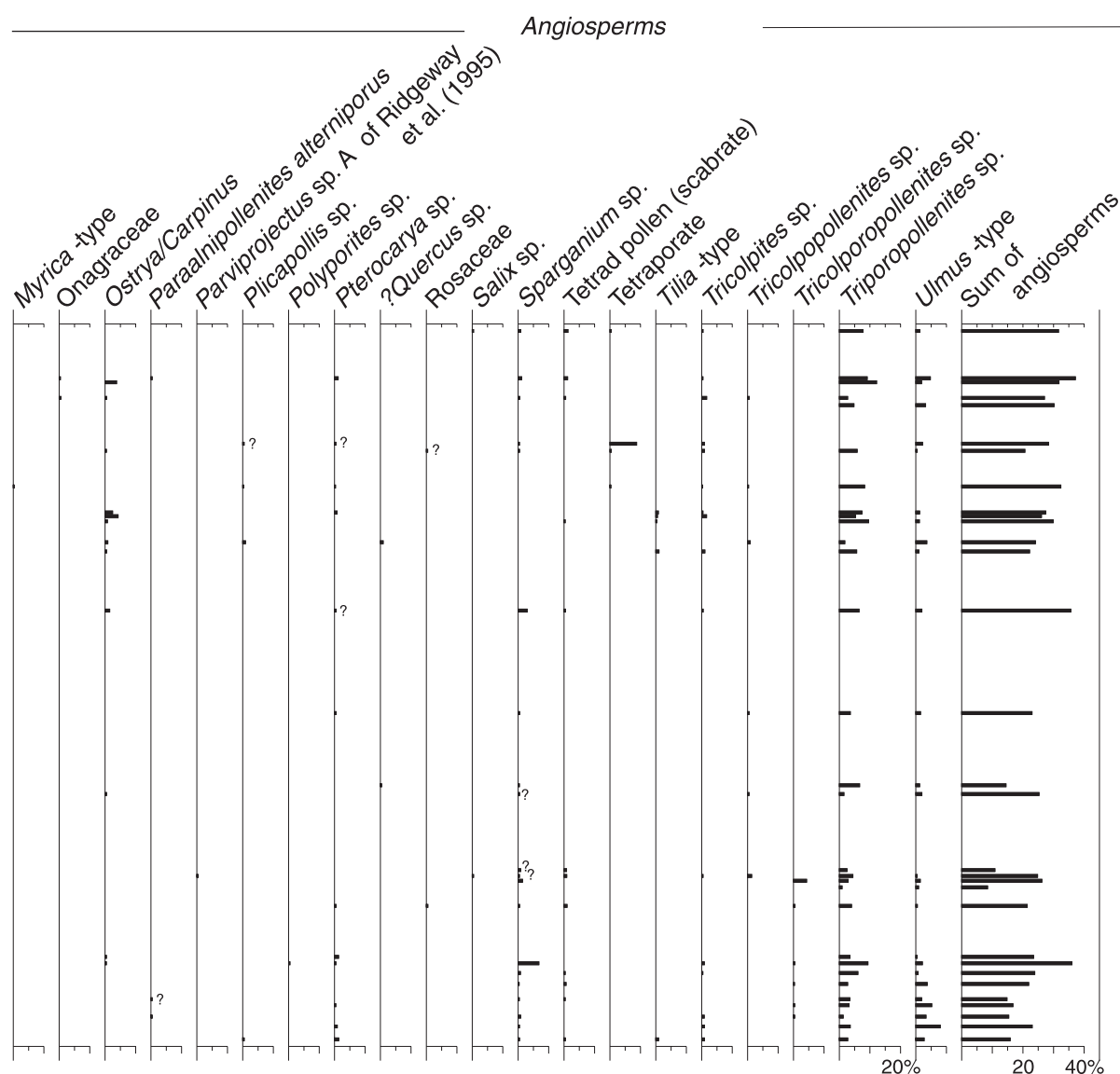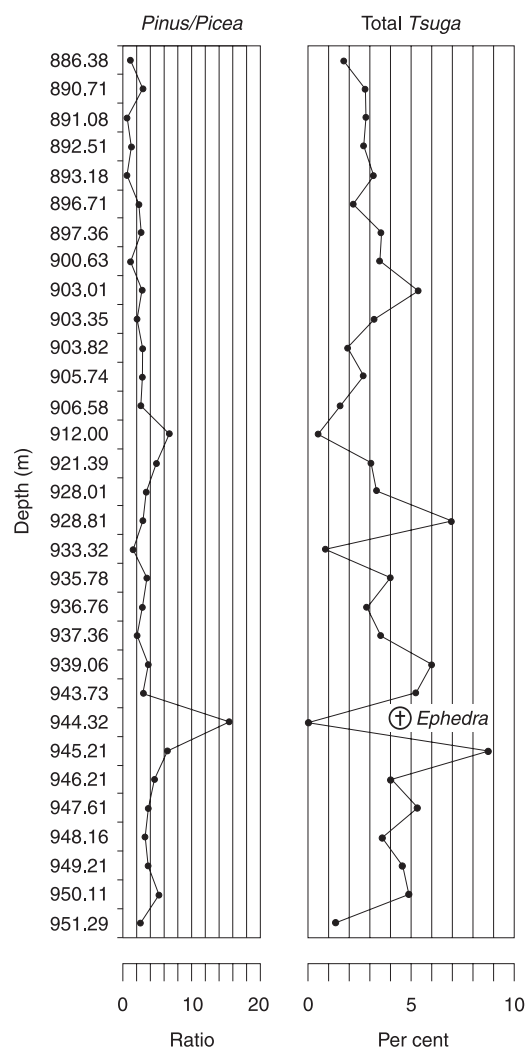


*Figure 5 (cont.)*

**Figure 6.** Pinus/Picea *ratio, percentage of* Tsuga *spp. and presence of* Ephedra *in 886–952 m cored interval. The high* Pinus/Picea *ratio, absence of* Tsuga *spp. and presence of* Ephedra *suggests an edaphic and/or climatic drought at 944.32 m in the Late Eocene, and a possible similar event at 912 m in the probable Late Eocene.*

more precise than the interpretation based on the dinoflagellates found in the well (Kurita and Uchida, 1999). These dinoflagellates should be interpreted as in place, rather than recycled. This analysis and that from Kurita and Uchida (1999) concur that the succession is largely continental, except for some marine incursion near 948–945 m, in the Late Eocene.

These results present the question of why the foraminifers are recycled, while the palynomorphs are largely not recycled. The answer seems to be in the depositional environment and sediment size fractions. Although much of the sediment is recycled from older, fossiliferous sedimentary rocks, the slow-settling silt to clay fraction, optimal for palynomorph recovery, must have been sufficiently exposed during transport to wind-borne, insect-borne, and aquatically transported pollen and spores that it picked up a strong contemporaneous

pollen and spore signature. In a mostly nonmarine environment, no contemporaneous foraminiferal signal was added to the sediment.

Fossils and age determinations below 930 m in the Mallik 2L-38 well imply that the enclosing rocks are best referred to the Richards and upper Taglu sequences, although it is not possible to more precisely identify comparable levels between the two wells. Sediments above 930 m are not as clearly identifiable to a sequence.

Two episodes of edaphic and/or climatic drought are suggested by the palynological record within the cored interval 886–952 m. One episode is in the Late Eocene, associated with a marine incursion, and one is probably in the Late Eocene.

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