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GEOLOGY AND BIOSTRATIGRAPHY OF THE DOME GULF ET AL. HUNT KOPANOAR M-13 WELL, BEAUFORT SEA

J. DIXON, D.H. McNEIL, J.R. DIETRICH,
J.P. BUJAK AND E.H. DAVIES

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GEOLOGY AND BIOSTRATIGRAPHY OF THE DOME GULF ET AL. HUNT KOPANOAR M-13 WELL, BEAUFORT SEA

Abstract

The Dome Gulf et al. Hunt Kopanoar M-13 well, which penetrated 4320 m of marine Tertiary strata, is situated in the Beaufort Sea, 78 km north of the Mackenzie Delta. An estimated 1900 m^3/day flow of oil from Eocene-aged sands, between 3525 and 3601 m, marks the first major oil discovery in a well located in the outer shelf area of the Beaufort Sea. The well is situated on a northwest-southeast trending, shale-cored anticline.

Reflection seismic data indicate that the borehole penetrated five depositional sequences (informally numbered 1 to 5 downwards) and that a sixth lies just below the total well depth. Syndepositional growth of the anticline was considerable during deposition of sequence 5 and continued through to sequence 2, but terminated prior to deposition of sequence 1.

Depositional sequence 1 consists of fine to coarse clastic sediments dated latest Miocene(?) to Pleistocene. Calcareous benthonic foraminifers, pollen and spores, dinoflagellates, and an abundance of reworked fossils, characterize this sequence. Seismic reflectors, dominated by conspicuous slope clinoforms, indicate sequence 1 is a progradational, slope to shelf succession.

Sequences 1 and 2 are separated by a regional unconformity at 2557 m, developed within Upper Miocene strata. Sequences 2 to 5 represent deep-water sedimentation, as indicated by the patterns of sedimentation, seismic facies, microfossil content, and regional geological setting. The deep-water regimes include base-of-slope, basin plain, and submarine fan environments. The sediments encountered are largely composed of clay- to silt-sized grains, but a number of sand-rich units also occur, one of which is the oil-bearing zone in sequence 5. Dinoflagellates from the upper part of sequence 2 indicate an age within the late Middle to Late Miocene; calcareous benthonic foraminifers recovered from sequences 2 and 3 indicate an age from Late Oligocene to Middle Miocene. Sequences 4 and 5 are rich in deep-water agglutinated foraminifers associated with a low-diversity palynomorph assemblage and are dated Eocene to Early or Middle Oligocene.

Résumé

Le puits Kopanoar M-13 de Dome, Gulf et al. Hunt a été foré à travers 4320 m de couches marines tertiaires dans la mer de Beaufort, à 78 km au nord du delta du Mackenzie. Environ 1900 m^3 par jour de pétrole sont extraits des sables de l'Éocène entre 3525 et 3601 m de profondeur; il s'agit de la première découverte importante de pétrole dans un puits situé dans la zone extérieure du plateau de la mer de Beaufort. Le puits se trouve sur un anticlinal orienté nord-ouest-sud-est, à centre schisteux.

Des données de sismique-réflexion montrent que le trou pénètre cinq séquences de sédimentation (numérotées officieusement 1 à 5 du haut en bas) et qu'une sixième séquence est sous-jacente au puits. La formation de l'anticlinal a eu lieu en même temps que l'accumulation de la séquence 5 et s'est poursuivie jusqu'à celle de la séquence 2; cependent, elle s'est terminée avant l'accumulation de la séquence 1.

La séquence 1 comprend des sédiments clastiques fins à grossiers qui datent du Miocène(?) récent au Plèistocène; elle est caractérisée par la présence de foraminifères benthoniques calcaires, de pollens et de spores, de dinoflagellés et d'abondants fossiles remaniés. Les réflexions sismiques dominées par des talus subaquatiques évidents démontrent que la séquence 1 représente une succession progradante du talus vers le plateau.

Les séquences 1 et 2 sont séparées, à une profondeur de 2557 m, par une discordance régionale dans les couches du Miocène supérieur. Les modèles de sédimentation, les faciès sismiques, les microfossiles et le milieu géologique régional portent à croire que les séquences 2 à 5 représentent la sédimentation en eau profonde. Les régimes d'eau profonde comprennent divers environnements comme le pied du talus, la plaine de remblaiement et le delta de canyon sous-marin. Les sédiments y sont généralement composés de grains dont la taille varie de l'argile au silt, ainsi que d'un certain nombre d'unités riches en sable, dont l'une est la zone pétrolifère de la séquence 5. Les dinoflagellés de la partie supérieure de la séquence 2 datent de la fin du Miocène moyen au Miocène récent; les foraminifères benthoniques calcaires des séquences 2 et 3 datent de l'Oligocène récent au Miocène moyen. Les séquences 4 et 5 sont riches en foraminifères agglutinants d'eau profonde associés à un assemblage peu diversifié de palynomorphes; elles datent de l'Éocène à l'Oligocène ancien ou moyen.

GEOLOGY AND BIOSTRATIGRAPHY OF THE DOME GULF ET AL.
HUNT KOPANOAR M-13 WELL, BEAUFORT SEA

INTRODUCTION

The Dome Gulf et al. Hunt Kopanoar M-13 well was drilled during the summers of 1977 and 1978, at 70°22'55.1"N, 135°05'33.9"W (Fig. 1), to a total depth of 4320.2 m (14 174 ft) below the kelly bushing (K.B.). Water depth at the well location was 57.3 m. Drill-stem testing took place in the summer of 1979 and significant quantities of oil and gas were recovered between 3525 and 3601 m (11 564 and 11 815 ft).

This report presents descriptions of stratigraphic units, their lithotypes and microfossils, and preliminary interpretations of their ages and depositional environments. The lack of lithological variation within the drilled succession is not conducive to identifying conventional lithostratigraphic units (i.e. formations), and the section has, therefore, been divided into depositional sequences (*sensu* Mitchum et al., 1977, p. 53). Depositional sequences were identified from reflection seismic profiles and geophysical well logs. Also, some sequences contain distinct microfossil assemblages, further aiding in their differentiation.

At least six major sequences can be identified on the seismic profile, of which five were penetrated in the M-13 well (Fig. 2). The sequences are informally numbered 1 to 6, youngest to oldest (Fig. 2). Sequence 6 occurs below the total depth of the M-13 well and consequently receives only a brief note in this report. Formal definition of the sequences is avoided for the present, as it is felt there is still insufficient knowledge of their age, distribution, lithological variation and correlation with the succession in the Mackenzie Delta. It should be noted, however, that some formal and informal stratigraphic terms for the Beaufort Sea succession have been published (Jones et al., 1980; Lane and Jackson, 1980; Hea et al., 1980; Willumsen and Coté, in press).

Curation of samples and type specimens

The samples used in this study are stored at the Institute of Sedimentary and Petroleum Geology, Calgary. Cutting samples and sidewall cores from the Dome Gulf et al. Hunt Kopanoar M-13 well are identified by GSC locality number C-76602 and the metres (feet) of the sampled section below kelly bushing.

Figure 1. *Location of Kopanoar M-13 and other offshore wells.*

All paleontological type specimens are assigned a unique GSC number and are stored in the type collection of the Geological Survey of Canada, Ottawa. The GSC type number of specimens illustrated in the report are listed in the captions for Plates 1 to 6.

Acknowledgments

We wish to thank A.F. Embry and F.M. Gradstein for their valuable comments and criticisms, and especially thank Dome Petroleum for allowing us to publish reflection seismic data for the Kopanoar M-13 well.

STRATIGRAPHY (J. Dixon and J.R. Dietrich)

Sequence 1

Sequence 1 in the M-13 well extends from the seabed to 2557 m (8390 ft) below K.B. This sequence can be divided into three seismic facies units (Figs. 2, 3). The upper unit extends from 0.08 to 1.0 secs. two-way travel time on the seismic reflection profile, which corresponds to the interval from the seabed down to approximately 975 m (3200 ft) log depth. Based on cutting samples and log characteristics in the Kopanoar M-13 and nearby Kopanoar D-14 wells, this upper unit contains weakly consolidated mudstone and siltstone, with some interbeds of fine- to coarse-grained sandstone and a few gravel beds (Fig. 3). Wood fragments and bivalve shells are abundant throughout the upper unit. On the seismic reflection profile the upper unit contains parallel reflections, which are known to grade basinward into slope clinoforms (not shown on Fig. 2). The reflection pattern, regional setting and lithotypes indicate a mid- to outer-shelf depositional environment for the upper unit.

The middle unit in sequence 1 extends from 1.0 to 2.1 secs. two-way travel time on the seismic profile (Fig. 2). These reflection times correspond to approximate log depths of 975 to 2256 m (3200-7400 ft). Reflection patterns consist of complex sigmoid-oblique clinoforms with hummocky patterns on some clinoforms. Toplap, downlap, hummocky reflections and internal convergence are also apparent. Weakly consolidated mudstone and siltstone form the bulk of the middle unit (Fig. 3). Sandstone beds containing wood fragments and shell debris are more common in the upper 305 m (1000 ft) of the unit. However, in the mudstone-dominant part of the succession, the presence of sand grains in the cutting samples, and a ragged gamma ray log trace, indicate the presence of numerous thin sandstone beds. The depositional setting was outer shelf to slope, as is clearly evident from the clinoforms seen on the seismic profile.

The lower unit in sequence 1 is between 2.1 and 2.33 secs. two-way travel time on the seismic profile (Fig. 2), corresponding to log depths 2256-2557 m (7400-8390 ft). Reflections within this unit are subparallel and discontinuous, and display southward onlap and northward (basinward) downlap. The succession consists of interbedded sandstone and mudstone (Fig. 3). Within this interval there is an upward decrease in the number and thickness of sandstone units. Individual sandstone units are up to 10 m thick, are mostly very fine- to fine-grained, locally coarse grained, and are weakly cemented. Reflection character, regional setting, and lithology indicate that the lower unit was deposited at the base of a shelf slope and on the basin plain. Sandstones within the lower unit are interpreted to be gravity flow deposits, probably consisting of turbidite beds.

In total, sequence 1 represents the building upwards and outwards of a shelf to basin plain sediment pile. The three units within sequence 1 can be interpreted in terms of responses to varying rates of sea level change, basin subsidence, or sediment supply. Prior to deposition of sequence 1 there was a major, basin-wide drop in sea level, recorded by the prominent unconformity below sequence 1 (Dixon and Snowdon, 1979; Jones et al., 1980; McNeil et al., 1982). The subsequent period of low stand in sea level is recorded by the lower unit of sequence 1, when sedimentation resulted in shelf margin onlap and basinward downlap. Rates of sediment supply were probably high during the low stand, due to erosion of the extensively exposed pre-sequence 1 rocks. Sea level during deposition of the lower unit was either at a still stand or rising very slowly. During deposition of the middle and upper units progradation was more pronounced than aggradation, as is evidenced by the clinoform reflections and the presence of toplap and internal convergences in the seismic reflections (Fig. 2). This type of sedimentation may occur during a period of moderate to rapid sea level rise, and/or basin subsidence, with relatively high rates of sediment supply.

Sequence 1 mudstones have a high content of carbonate minerals (3-14%), mostly calcite and dolomite, in contrast to the mudstones of the older sequences. The carbonate occurs as dispersed authigenic cement, or as discrete micronodules and submicroscopic sheet-like forms (Dixon et al., 1982). X-ray analysis of the mudstones indicates that quartz is the dominant mineral (63-80%), with clay minerals as a subdominant component (11-22%).

Sequence 1 rocks are earliest Pliocene, possibly as old as latest Miocene, to Holocene in age (see later discussion). The oldest age indicated differs from that suggested by some other authors. Lane and Jackson (1980, figs. 5, 6 and 7) implied a Late Oligocene age for the oldest sediments in strata equivalent to sequence 1 (their Beaufort sequence)[1]. Jones et al. (1980), whose Iperk Group is equivalent to sequence 1, indicated a Miocene to Recent age, implying that the whole of the Miocene was represented by part of the Iperk succession. Hea et al. (1980, figs. 15 and 24) also indicated that strata equivalent to sequence 1 were deposited throughout the whole of the Miocene (their Beaufort Formation[1] and seismic unit Tu). The microfossils present in sequence 1 of the Kopanoar M-13 and Ukalerk C-50 (McNeil et al., 1982; Bujak and Davies, 1981)[2] wells suggest that most of the strata are Pliocene-Pleistocene and Holocene in age, with possibly some uppermost Miocene strata in the basal part of the sequence.

The boundary between sequences 1 and 2 is a major regional unconformity (see also Dixon and Snowdon, 1979; Jones et al., 1980; McNeil et al., 1982) and is readily identified on the sonic log as an abrupt reduction in velocity (higher sonic transit time) across the boundary (Fig. 3).

[1]The Beaufort Formation/sequence as used by Lane and Jackson (1980) and Hea et al. (1980) does not correspond to the Beaufort Formation as used by Young et al. (1976) and expanded upon by Young and McNeil (in press).

[2]The well referred to as Hunt Dome Kopanoar M-13 in Bujak and Davies's paper is the same as the Dome Gulf et al. Hunt Kopanoar M-13 of this paper.

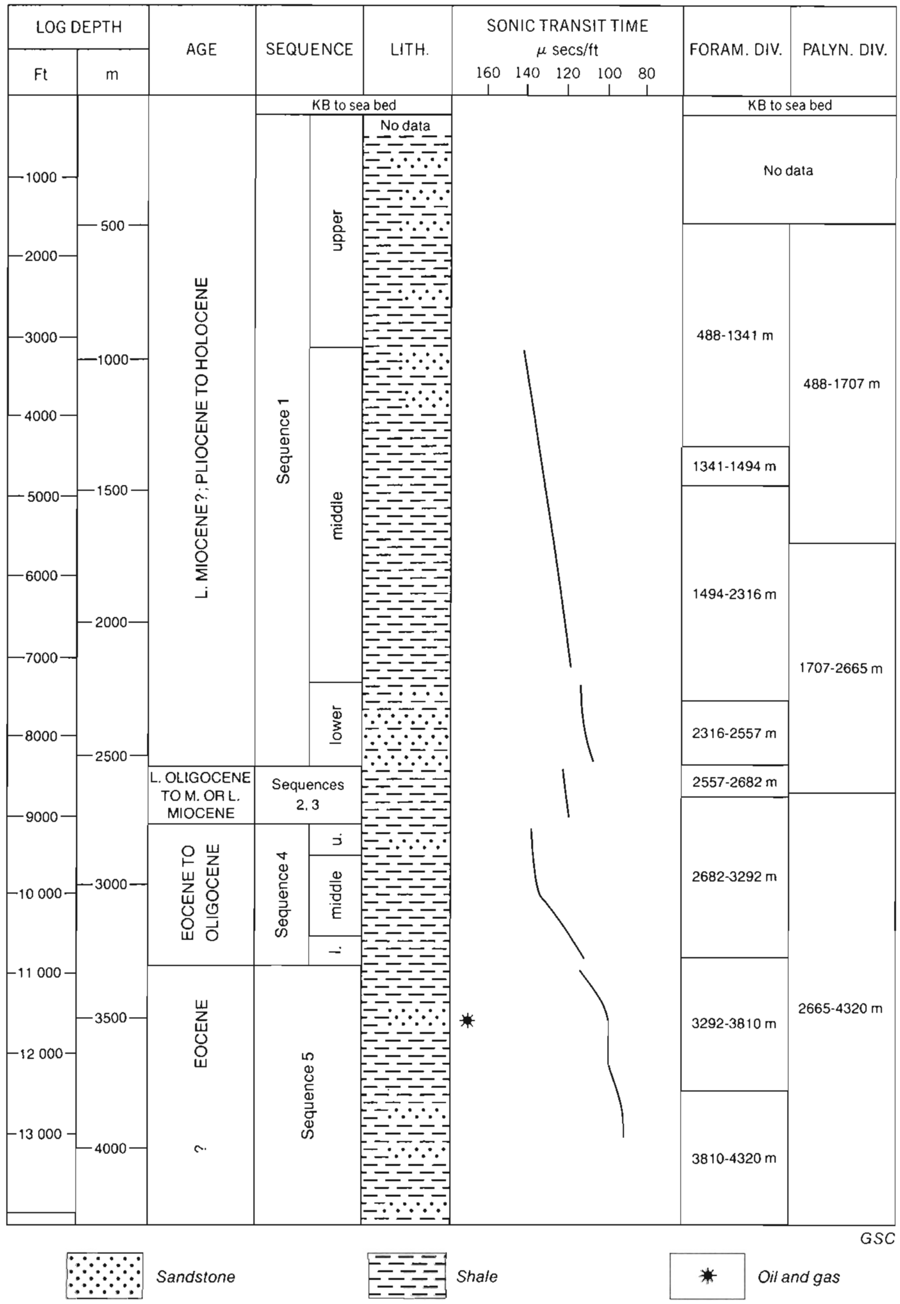

Figure 3. *Summary of geological data and a depth-sonic transit time plot.*

McNeil et al. (*op. cit.*, p. 3) speculated that the unconformity may reflect the Late Miocene eustatic drop in sea level reported by Vail et al. (in Mitchum et al., 1977). It may correlate also with the Late Miocene regional unconformity in the Labrador Shelf and Baffin Bay regions, as recognized by McWhae (1981).

Sequences 2 and 3

Sequences 2 and 3 occur between 2557 and 2785 m (8390 and 9138 ft), which, on the seismic profile (Fig. 2), is between 2.33 and 2.5 secs. two-way travel time. It is unclear from the seismic data if sequence 3 extends over the Kopanoar structure through the M-13 location (Fig. 2). Also, there are no distinct lithological or log character changes within the interval to suggest a sequence boundary. However, the foraminiferal assemblage between 2682 and 2785 m (8800 and 9138 ft) is correlative with known sequence 3 strata in other parts of the basin. The base of sequences 2 and 3 was determined primarily from a reflection time-depth conversion and tentatively correlated with a minor velocity and gamma-ray log marker at 2785 m (9138 ft) (on logs of runs 4 and 5).

The seismic profile (Fig. 2) clearly shows that the M-13 well penetrated only a thin section of sequence 2 and 3 strata. The dramatic south to north thinning of these sequences is a combination of basinward thinning, syndepositional growth of the Kopanoar structure and possibly some erosion prior to deposition of sequence 1. Both sequences contain downlapping, sigmoid clinoforms, and sequence 3 has mounded and draped reflectors, evident between shotpoints 350 to 550 (Fig. 2).

The sediment in the sequences is predominantly silty to sandy mudstone with some very thin sandstone interbeds (the latter are interpreted to be present from the amount of sand in the cutting samples; Fig. 3). Traces of carbonate fragments were noted in the cutting samples between 2557 and 2621 m (8390 and 8600 ft). The mudstones in sequence 2 do not contain much carbonate material; consequently, the carbonate fragments are believed to be from discrete concretions. As well as a lack of carbonate minerals, the mudstones of sequence 2 have up to 4 per cent pyrite. These two lithological features can be used to differentiate sequence 2 from sequence 1 mudstones.

The reflection patterns, regional setting, microfossils and lithology point to deposition at the base-of-slope and basin plain area for sequences 2 and 3.

Sequences 2 and 3 are latest Oligocene to late Middle or Late Miocene in age.

Sequence 4

Sequence 4 occurs between 2785 and 3339 m (9138 and 10 956 ft), which corresponds to 2.5 to 2.95 secs. two-way travel time on the seismic reflection profile (Fig. 2). The exact base of sequence 4 is problematic. On the sonic log there is a distinct character change at 3350 m (10 992 ft), whereas on the dual induction log the character change occurs at 3354 m (11 004 ft). There is also a minor change in abundance of foraminifera at about 3353 m (11 000 ft). Whichever of these changes reflects the true sequence boundary, it is apparent that a major stratigraphic boundary is present somewhere between 3339 and 3354 m.

Based on the gamma ray, sonic and induction log characteristics, sequence 4 can be divided into 3 units. The upper unit occurs between 2785 and 2899 m (9138 and 9512 ft), the middle unit between 2899 and ?3225 m (9512 and ?10 582 ft), and the lower unit between ?3225 and 3339 m (?10 582 and 10 956 ft). Mudstone is the dominant lithology throughout sequence 4, but appears to be more abundant in the lower and upper units (Fig. 3). Medium- and coarse-sized sand grains are common in the cutting samples, although the log characteristics do not indicate the presence of thick sandstone beds, suggesting that most of the sand must occur in thin beds. Pyrite is a common accessory mineral and is readily spotted in the cuttings.

Sequence 4 contains discontinuous, shingled and hummocky reflectors. They represent the downlapping bottomset portions of clinoforms, located to the south of the seismic profile. These reflection characters, along with the lithology and microfossils of sequence 4, indicate a base-of-slope to basin plain depositional environment.

The age of sequence 4 is considered to be Eocene to Oligocene.

Sequence 5

Sequence 5 begins at 3339 m (10 956 ft) and extends below the total depth (4320.2 m) of the M-13 well. The base of the sequence is estimated to be at about 4359 m (14 300 ft). On the seismic reflection profile, sequence 5 occurs between 2.95 and 3.6 secs. two-way travel time (Fig. 2). Reflectors within the sequence are subparallel to mounded.

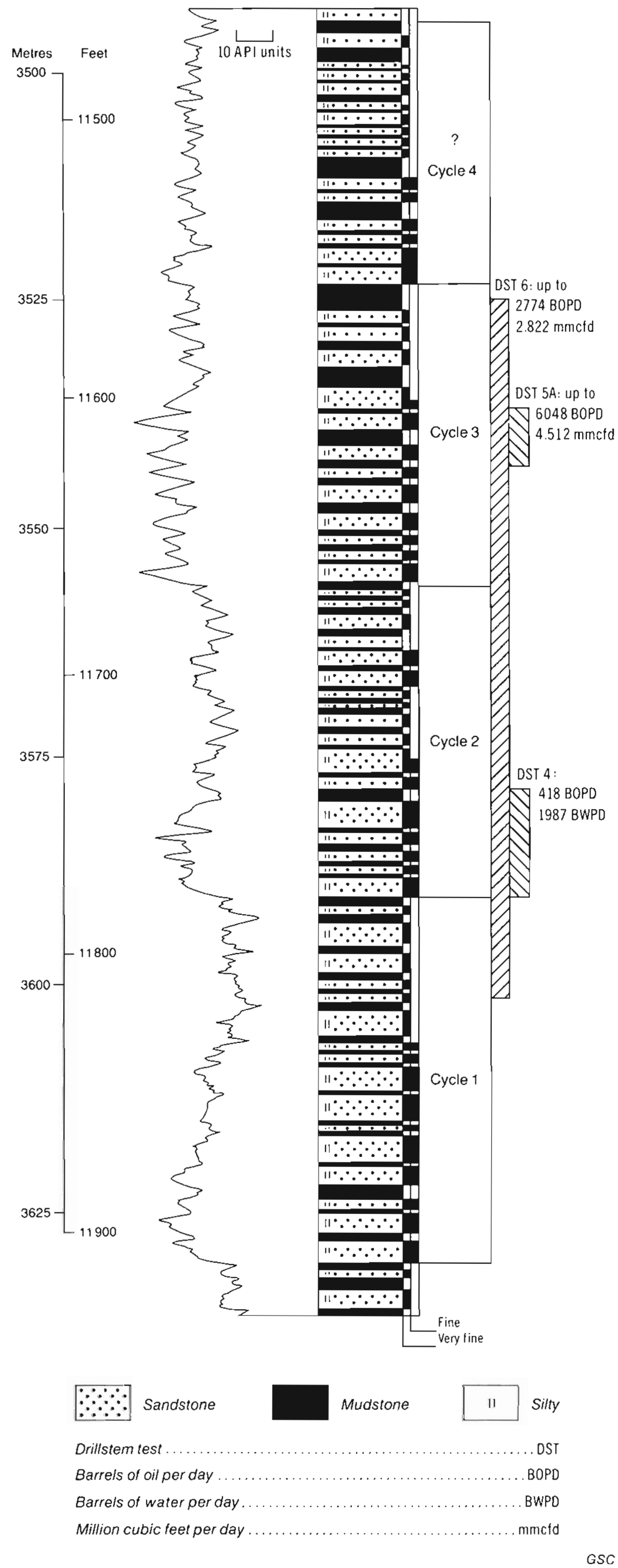

Figure 4. *Lithological and gamma-ray log characteristics of the uppermost sandstone interval in sequence 5 (3496.1-3630.2 m; 11 470-11 910 ft).*

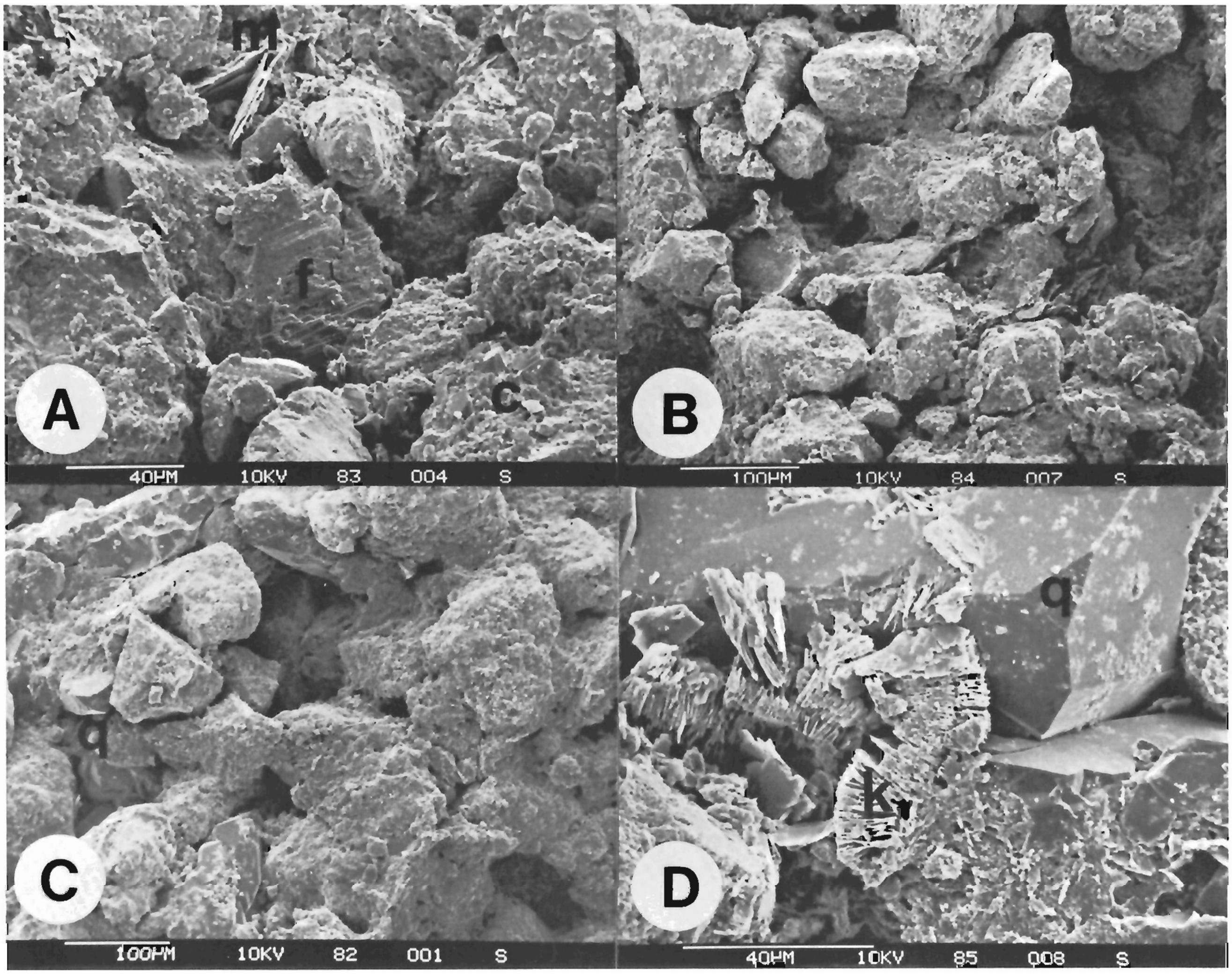

Figure 5. *SEM photographs of sandstones recovered from sequence 5:*

A) *Cutting sample recovered from between 3532.6 and 3560.1 m (11 590 and 11 680 ft). Poorly sorted sandstone containing grains of quartz/chert (c) (note the small quartz overgrowths), feldspar (f) and mica (m).*

B) *Cutting sample recovered from between 3618 and 3630.2 m (11 870 and 11 910 ft). Similar composition to that in 5A. Note the matrix of clay- to silt-size material.*

C) *Cutting sample recovered from between 3901.4 and 3922.8 m (12 800 and 12 870 ft). Moderately well sorted sandstone, consisting of subangular to subrounded grains of chert and quartz; some of the latter have authigenic overgrowths (q).*

D) *Cutting sample recovered from between 4191 and 4206.2 m (13 750 and 13 800 ft). Kaolinite (k) and quartz with authigenic overgrowths (q) are common in this sample.*

The sediments are predominantly mudstones and siltstones, but within the drilled part of the sequence there are four sandstone-rich intervals (Fig. 3), at 3496-3630 m (11 470-11 910 ft); 3863-3941 m (12 674-12 930 ft); 4000-4083 m (13 122-13 395 ft), and 4160-4279 m (13 648-14 038 ft). The uppermost of these sandy intervals tested oil and gas, the lower three appear to be water-bearing (based on log character).

The hydrocarbon-bearing sandstones between 3496 and 3630 m are not well defined on most of the geophysical logs. However, the gamma-ray log does suggest the presence of several fining-upward cycles (Fig. 4). The gamma-ray log character indicates that the cycles are composed of numerous thin units, most of which are generally less than 5 m thick. The sandstones are very fine- to fine-grained and weakly cemented to unconsolidated. A few rock chips were recovered from the cutting samples and examined by electron microscope. These samples were of poorly sorted sandstone containing angular to subangular grains of quartz, chert and feldspar, with significant amounts of detrital mica and clay (figs. 5A, B). There appears to have been very little diagenetic change in these sandstones, only minor amounts of quartz overgrowth were noted, mostly on chert grains (Fig. 5A).

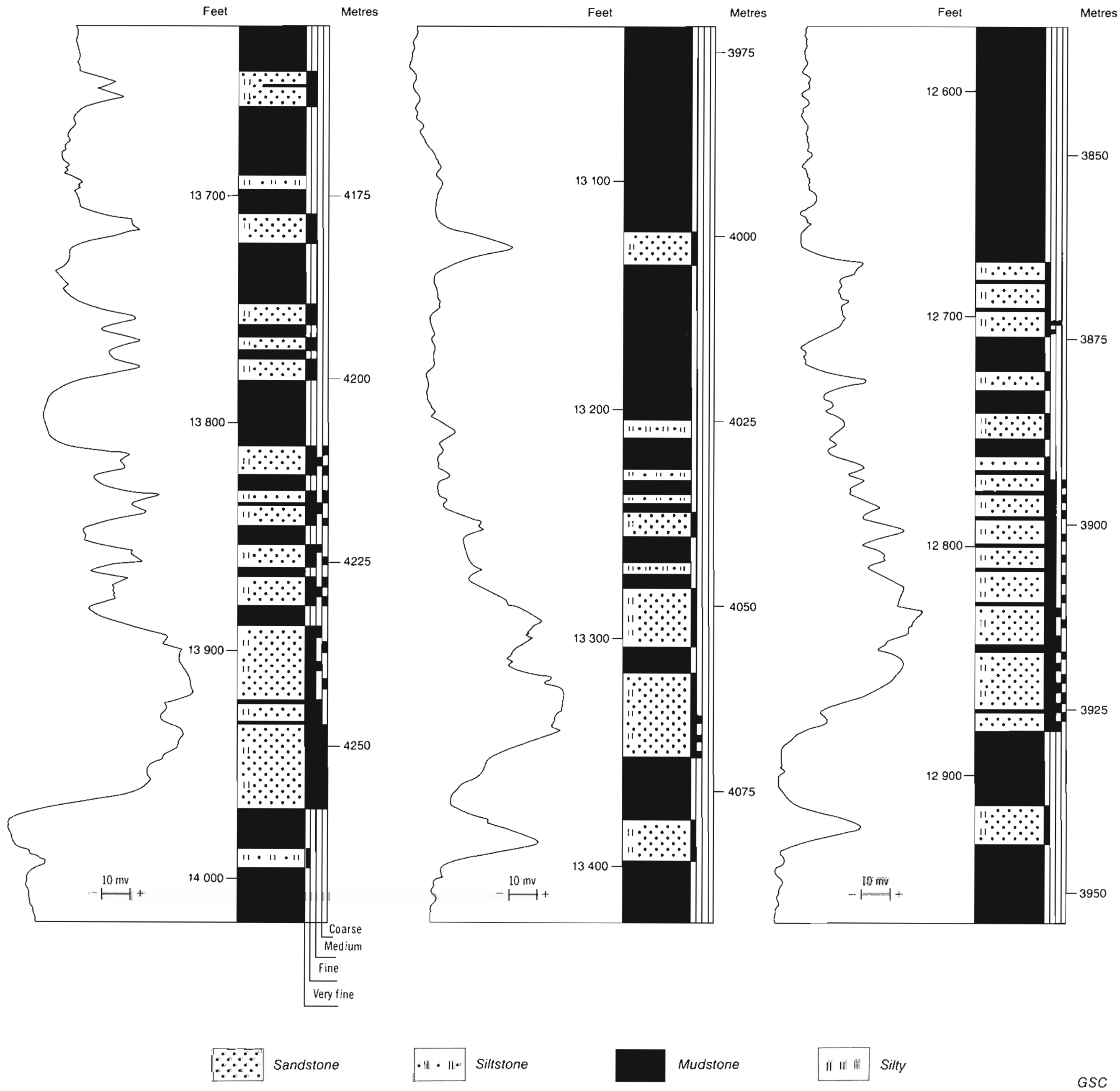

Figure 6. *Lithology and SP log (inverted) character of the lower sandstone intervals in sequence 5.*

The other three sandstone-rich intervals have a more pronounced log response and all show several common features, namely (Fig. 6):

1. An overall fining-upward trend.
2. Sandstone units decrease in thickness upwards.
3. Mudstone intervals increase in thickness and number upwards.
4. Each sandstone-rich interval is underlain by a thin sandstone or siltstone bed.
5. The lowest, and generally thickest, sandstone unit appears to have an abrupt basal contact.

Each of the three lower intervals appears to contain between 40 and 60 per cent sandstone (based on log response). Sand grain size ranges from very fine to coarse in the lowest and uppermost intervals, and very fine to fine in the middle interval. Most of the sandstones are poorly to moderately well sorted, weakly cemented to unconsolidated, and consist of angular to subangular grains of quartz and chert, with minor amounts of feldspar and detrital mica (Fig. 5C). Authigenic minerals are more common in the lower sandstone units than in the beds at 3496 - 3630 m, but still not volumetrically important, and consist of quartz overgrowths and kaolinite (Fig. 5D).

The regional setting, reflection patterns, microfossils and lithology indicate a deep-water origin for sequence 5 rocks. The lower three sandstone-rich intervals have a number of characteristics in common with Ricci-Lucchi's (1975), "complex-composite, fining-upward (+) cycles", in turbidite successions. Ricci-Lucchi (*op. cit.*) interpreted such cycles as consisting of channel-sands (deposited on the inner or middle part of a submarine fan) at the base of each cycle, overlain by outer fan to basin plain turbidites. Each cycle would be bounded above and below by hemipelagic and/or chaotic slope deposits. Walker (1978) attributed similar fining-upward cycles of submarine fans to three possible mechanisms: channel filling on the upper fan, channel filling on the supra-fan, or the filling of an incised channel on the lower fan. The uppermost sandstone-rich interval in sequence 5 differs from the lower three in that both the fining-upward cycles and the individual sandstone beds are thinner. These characteristics suggest that the uppermost interval sandstones represent small channel fills, possibly braided channels, on the lower fan or distal part of the middle fan.

Microfossils recovered from the upper part of sequence 5 indicate an Eocene age. The section below 3719 m (12 200 ft) was essentially barren, but is dated as Eocene on the basis of seismic correlations with established Eocene sections elsewhere in the basin.

KOPANOAR STRUCTURE (J. Dixon and J.R. Dietrich)

The M-13 well was drilled into a large WNW-ESE trending, shale-cored, diapiric anticline. This structure is part of an extensive development of similarly oriented shale diapirs in the central and western Beaufort-Mackenzie Basin (Young et al., 1976). The seismic profile indicates that there was syndepositional growth of the Kopanoar anticline (Fig. 2). Little or no structural growth of the anticline can be detected during deposition of sequence 6. There was considerable growth during deposition of sequence 5, evident from the pronounced depositional thinning of these rocks over the anticline. Diapiric growth continued sporadically, but with less intensity, during deposition of sequences 4 to 2, and terminated prior to deposition of sequence 1.

At the northern end of the seismic profile, at about 6.8 to 7.0 secs. two-way travel time (Fig. 2), there are several prominent planar reflections. Above the planar reflections the upturned limits of the Kopanoar anticline are readily seen. It would appear that these planar reflections represent a structural basement above which structures are detached. The nature and age of the rocks forming the structural basement are not known.

BIOSTRATIGRAPHY (D.H. McNeil, J.P. Bujak and E.H. Davies)

Introduction

Biostratigraphic analysis of cuttings and sidewall cores from the Kopanoar M-13 well has resulted in a preliminary zonation consisting of six foraminiferal and three palynological assemblage zones. The sampled section begins at 488 m (1600 ft) and continues to total well depth at 4320 m (14 173 ft). Collectively, the assemblages range in age from Eocene to Pleistocene. Much of the section sampled represents sedimentation in deep, probably bathyal, water. As such, the Kopanoar M-13 section stands in contrast to the marine shelf and terrestrial sections, which have been previously studied in the area of the Mackenzie Delta (e.g. Staplin, 1976; Young and McNeil, in press; McNeil et al., 1982). Thus, Kopanoar M-13 serves as an important reference section for the deeper water faunal and floral distribution patterns. In so far as the main objective of this paper is to document the succession in the Kopanoar well, biostratigraphic correlations through the Beaufort Sea subsurface and beneath the Mackenzie Delta are minimal.

The section is divided by a major unconformity at 2557 m (8390 ft) which, as discussed earlier, serves not only to partition the Kopanoar succession, but also forms a regional marker in the Beaufort Sea. The unconformity has previously been determined as a Late Miocene event (McNeil et al., 1982), based on foraminiferal and palynological considerations and on deduction from the timing of major tectonic, climatic, and oceanographic events in the mid-Cenozoic. Independent support for this age has come from the recognition of late Middle to Late Miocene dinoflagellates just below the unconformity (Bujak and Davies, 1981, and this paper).

The section below 2557 m consistently represents deep-water sedimentation, though the precise depths of water and nature of the depositional regimes are still very much open to interpretation. Small calcareous benthic foraminifers are dominant from 2560 to 2682 m (8400 to 8800 ft); agglutinated foraminifers with minor calcareous benthic species are characteristic from 2682 to 3292 m (8800 to 10 800 ft); and agglutinated species prevail from 3292 to about 3810 m (10 800 to 12 500 ft). The section below 3810 m to total well depth is essentially barren of foraminifers.

The palynological succession below 2557 m (8390 ft) is highlighted by an important zone of dinoflagellates from 2584 to 2665 m (8477 to 8744 ft), dated late Middle to Late Miocene, corresponding to nannoplankton zones NN7 to NN11. The documentation of this dinoflagellate zone is a significant contribution to chronostratigraphic resolution in the Beaufort Sea, marking the first substantial link to the standard marine zonal scheme. Below 2665 m, the palynomorph recovery is dominated by pollen and spores, with a progressive downhole decrease in relative abundance, perhaps caused by the addition of tracheids, cuticle, and other herbaceous matter, introduced to the deep marine environment from terrestrial source areas to the south.

The biotic succession above the Late Miocene unconformity at 2557 m differs markedly from that below. A zone containing abundant reworked foraminifers from 2316 to 2557 m (7600 to 8390 ft) is overlain by a largely barren zone from 1494 to 2316 m (4900 to 7600 ft). Above 1494 m, to the top of the sampled section at 488 m (1600 ft), Pliocene to Pleistocene calcareous benthic foraminifers are common to abundant. Palynological assemblages above the unconformity are also marked by a zone of abundant reworked palynomorphs, from 1707 to 2557 m (5600 to 8390 ft), with associated indigenous dinoflagellates which suggest a Late Miocene age. It has been estimated that as much as 95 per cent of the palynomorphs recovered from 488 to 1707 m are reworked from much older strata, but indigenous palynomorphs, including algal cysts, coniferous pollen, and several dinoflagellates, may be identified through fluorescent microscopy.

FORAMINIFERS (D.H. McNeil)

Division 488-1341 m (1600-4400 ft)

Division 488-1341 m is distinguished by common to abundant occurrences of **Elphidium clavatum** Cushman, **E. asklundi** Brotzen, **E. ustulatum** Todd, **Elphidiella hannai** (Cushman and Grant), **Protelphidium orbiculare** (Brady), **Cassidulina reniforme** Nørvang, and **C. teretis** Tappan (Fig. 7). Rare to abundant reworked foraminifers, probably of Early Cretaceous age, are also characteristic of this division. Foraminiferal recovery decreases markedly at 823 m (2700 ft); species occurrences below that level to 1341 m may represent caved cuttings. The abundance of **E. clavatum** from 488 to 823 m suggests cold, low-salinity, marine water, probably within the inner shelf. An undifferentiated Pliocene to Pleistocene? age is tentatively assigned to division 488 to 1341 m.

The foraminiferal assemblage of division 488-1341 m is widespread over the Beaufort Sea and Mackenzie Delta areas. It compares with the Pliocene-Pleistocene assemblage of division 745-1066 m in the Ukalerk C-50 well to the southwest, described by McNeil et al. (1982), and toward the Delta it compares with the inner shelf **Elphidium** spp. assemblage of Young and McNeil (in press), and the **Sigmopolis**-ostracode-**Elphidium** assemblage of Staplin (1976).

Division 1341-1494 m (4400-4900 ft)

Abundant **Cassidulina teretis** Tappan and **Cibicides grossa** ten Dam and Reinhold, and common **Virgulina loeblichi** Feyling-Hanssen and **Melonis barleanum** (Williamson), readily distinguish division 1341-1494 m, and mark a pronounced shift in the faunal spectrum. On the basis of seismic interpretation, the contrast is one between slope facies (1341-1494 m) and shelf facies (upper fossiliferous part of division 488-1341 m). Precise water depths are probably not obtainable from the foraminiferal data alone, although **C. teretis** and **V. loeblichi** indicate normal marine conditions, offshore relative to the upper part of division 488-1341 m, which carries an **Elphidium clavatum** dominated assemblage indicative of a low-salinity, cold-water environment.

The occurrence of **C. grossa** through division 1341-1494 m is noteworthy. The species is a common constituent of Miocene and Pliocene assemblages in the North Sea Basin and the Canadian Arctic Islands. Its distribution was recently summarized by Feyling-Hanssen (1980, p. 169-170). In northwest Baffin Island, **C. grossa** was chosen by Feyling-Hanssen as the nominative species for a distinctive zone, dated Pliocene, and signifying arctic-boreal climatic conditions. The zone was characterized also by **Nonion erucopsis, Cassidulina teretis, Elphidium subarcticum, E. excavatum, Protelphidium orbiculare**, and **Cassidulina subacuta.** Whether or not the zone should be extrapolated as far as the Beaufort Sea is uncertain, but little doubt exists about the broad homotaxial similarity of the Pliocene faunal successions between the two areas.

The abundance of **C. teretis** in division 1341-1494 m suggests correlation to the upper half of division 1249-1569 m in the Ukalerk C-50 well. **C. grossa** was not recovered from Ukalerk C-50, but the faunal succession is very similar in general and the preceding correlation seems well justified. Farther to the south and shoreward, no equivalent assemblages have been recovered, probably due to the southward wedge-out of the slope facies.

Division 1494-2316 m (4900-7600 ft)

Division 1494-2316 m is largely barren of foraminifers. A Late Miocene to Pliocene age is tentatively assigned on the basis of palynological determinations. The few specimens of foraminifers recovered (Fig. 7) are no doubt largely derived from caved well-cuttings. A barren zone of such an extent, 823 m, is a striking feature and warrants consideration of its cause. Seismic interpretation for this section indicates a lower slope - continental rise, depositional sequence. Comparison of this deep-water sequence with equivalents under the modern Beaufort Sea may offer some explanation. Vilks et al. (1980) documented the distribution patterns of Holocene foraminifers beneath the Beaufort Sea. Regarding the continental rise environment, they noted (*op. cit.*, p. 18) that the low diversities encountered probably resulted from low nutrient supply and high rates of sedimentation.

Division 2316-2557 m (7600-8390 ft)

Like the overlying section, division 2316-2557 m is barren of *in situ* foraminifers. This unit, however, is clearly distinguished by the consistent recovery of abundant reworked siliceous foraminifers, probably of Early Cretaceous age. Reworked, siliceous foraminifers are a characteristic feature of the Late Miocene(?) to Pleistocene section in the Beaufort Sea (McNeil et al., 1982), and in the Pliocene-Pleistocene Nuktak Formation of the neighbouring Mackenzie Delta (Young and McNeil, in press). The occurrence of reworked foraminifers in this division and in division 488-1341 m, but not in the intervening divisions 1341-1494 m and 1494-2316 m, may be explained by the redistribution of the siliceous foraminifers from the shelf regions into the bathyal environment, effectively bypassing the slope and upper continental rise. This interpretation relies to a large degree on the seismic data and regional setting, which reveal that much of this section consists of downlapping seismic reflections, suggesting base of slope and basin plain deposits. The absence of redistributed, calcareous, benthic species may be due to dissolution of the more soluble calcareous tests and selective preservation of the more sturdy siliceous tests. Alternatively, it may be that the fan deposits are chiefly derived from nearshore, river-dominated environments, which were devoid of calcareous foraminifers.

Division 2557-2682 m (8390-8800 ft)

The unconformity at 2557 m, below sequence 1, marks the upper boundary of division 2557-2682 m, which contains a distinctive, calcareous, benthonic, foraminiferal assemblage dated latest Oligocene to Middle or Late Miocene. The assemblage consists of common to abundant **Eponides binominatus** Subbotina and rare **Valvulineria petrolei** (Andreae), **Pullenia bulloides** (d'Orbigny), **Miliolinella circularis** (Bornemann), **Globocassidulina subglobosa** (Brady), **Trifarina fluens** (Todd), **Asterigerina guerichi** s.l. (Franke), **Turrilina alsatica** Andreae, **Pullenia** cf. **P. quinqueloba** (Reuss), and **Bathysiphon cylindrica** (Glaesner). The assemblage is widespread in the strata beneath the Beaufort Sea and representative species from the Ukalerk C-50 well, were illustrated by McNeil et al. (1982), and from the outer Mackenzie Delta, chiefly in the Mackenzie Bay Formation, by Young and McNeil (in press). Previous descriptions of the assemblage were from shelf or upper slope facies. The Kopanoar M-13 biofacies, in contrast, is the deep-water expression of the assemblage.

The calcareous foraminifers of division 2557-2682 m are small (maximum diameters range from 0.08 mm to 0.30 mm; average specimen diameter is 0.16 mm) and generally unornamented, with the exception of **Trifarina fluens**, which shows well developed longitudinal costae, a feature typical of uvigerinids in deep waters (Douglas, 1979). The strongly ornamented **T. fluens** of the Kopanoar M-13 well contrasts markedly with the relatively smooth surfaced **T. fluens** from the Ukalerk C-50 well and from the Richards Island area (McNeil et al., 1982; Young and McNeil, in press). The small specimen size of the Kopanoar M-13 foraminifers in division 2557-2682 m is reminiscent of modern deep-water arctic assemblages, which Lagoe (1977) interpreted as resulting from low availability of $CaCO_3$.

Division 2557-2682 m also contains dinoflagellates indicating correlation with nannoplankton zones NN7 to NN11, or late Middle to Late Miocene (Fig. 8). Based mainly on foraminiferal considerations for the Ukalerk C-50 well, McNeil et al. (1982) assigned an Early to Middle Miocene age to the **Asterigerina guerichi** s.l. part of this assemblage, and a Late Oligocene age to the part with **Turrilina alsatica.** These determinations are extrapolated to Kopanoar M-13, to the 2557-2652 m and 2652-2682 m intervals respectively. The Early to Middle Miocene foraminiferal age determination for Ukalerk C-50 and Kopanoar M-13 is thus generally compatible with the dinoflagellate age determination in Kopanoar M-13. It is apparent from biostratigraphic and seismic evidence that division 2557-2682 m is a thin, mostly Miocene section, developed on a deep-basin high, and is much condensed compared to its slope and shelf equivalents to the south.

Division 2682-3292 m (8800-10 800 ft)

Agglutinated foraminifers are the principal components of the assemblage in division 2682-3292 m. The division also contains rare calcareous benthic species, particularly in the upper part, from 2682 to 2926 m (8800-9600 ft).

The assemblage is dominated by the following species (Fig. 7 and Plates 1-3): **Bathysiphon nodosariaformis** Subbotina, **B. cylindrica** (Glaesner), **B. pseudoloculus** (Myatliuk), **Haplophragmoides** cf. **H. carinatus** Cushman and Renz, **Recurvoides** cf. **R. contortus** Earland, **R.** cf. **R. turbinatus** (Brady), **Alveolophragmium (Reticulophragmium) amplectens** (Grzybowski), **A. (R.) rotundidorsata** (Hantken), **A. (R.)** sp. 1, **A. (R.)** sp. 2. Rare occurrences of species of **Jaculella, Ammolagena, Ammodiscus, Saccamminoides**(?), **Rzehakina, Haplophragmoides, Trochammina,** and **Cystammina** constitute the remainder of the assemblage.

The continuity of occurrence for the longer ranging species and the gradual downhole introduction of species imply that division 2682-3292 m, as well as the underlying division 3292-3810 m, represent fairly uniform, or only slightly varying, sedimentary environments. Seismic data for this section indicate a lower slope to rise regime. The composition of the foraminiferal assemblage suggests deep-water environments also, but an interpretation of paleo-water-depth based solely on agglutinated foraminifers is generally not conclusive in outer shelf and deeper-water environments. The nature of the assemblages and their potential for preservation are controlled by other environmental factors, some of which may indirectly provide depth interpretations. Gradstein and Berggren (1981) have recently discussed the characteristics and significance of agglutinated foraminferal assemblages at some length, concluding that agglutinated faunas, similar to those reported here, range from the outer shelf to the abyssal, and that the availability or the stability of $CaCO_3$ is a determining factor in the final composition of the assemblage.

Rare calcareous benthic specimens occur throughout division 2682-3292 m, but their significance is suspect due to the possibility of caved well-cuttings. Factors in favour of *in situ* derivation include the fact that the uppermost occurrence of several species is located within the division, and there is a marked contrast in preservation between the calcareous species from this division and the overlying one. The calcareous benthics of division 2557-2682 m are well preserved despite having fairly thin-walled, delicate tests. Beginning at 2865 m (9400 ft) and downwards there is a marked deterioration in preservation, most specimens being corroded and rusty remnants of the original test. Specimens that were obviously caved from above the unconformity at the base of sequence 1 are well preserved in the downhole cuttings. Although not conclusive, the preservational differences suggest that the corroded specimens of division 2682-3292 m represent a partially decalcified component of a mixed, calcareous-agglutinated, foraminiferal assemblage, truly representative of at least the upper part of division 2682-3292 m, where several first downhole occurrences were recorded.

The chronostratigraphic interpretation of this division is difficult to resolve with certainty for several reasons. Many of the species, or the form to which they are compared, are long ranging (some to the Recent), and are thus meaningless for chronostratigraphic refinement. Others are apparently endemic and new, such as **Alveolophragmium (R)** sp. 1 and 2, and cannot be dated except by comparison with another index. Further, the ranges of many of the species may be different in the Arctic region than, for example, in the North Atlantic. Additionally, there is a general lack of other indices, such as planktonic foraminifers, nannofossils or palynomorphs, that might help to substantiate the determinations based on foraminiferal data. The following age determinations are thus provisional.

Tentatively, a Late Eocene to Early or Middle Oligocene age is assigned to division 2682-3292 m. The Oligocene-Eocene boundary cannot be located with assurance, but is thought to occur at 2865 m (9900 ft), marked by the first common downhole occurrences of **A. (R.) amplectens**, a well known index of the Eocene in the east Canadian margin, the North Sea, and the Carpathian Mountains of central Europe (Gradstein and Berggren, 1981). The upper part of the division is dated Oligocene on the basis of rare occurrences of **T. alsatica.** The rare occurrence of **A. (R.) amplectens** between 2835 and 2926 m (9300-9600 ft) is interpreted to represent an extension of the range of this species into the Early Oligocene. Lower in the section, the occurrence of **Trochammina subvesicularis** Homola and Hanzlîhovâ in association with **A. (R.) amplectens**, between 3018 and 3292 m (9900-10 800 ft), indicates an extension of the range of **T. subvesicularis** into the Eocene. Previously, it was not known to range higher than the Paleocene (Gradstein and Berggren, 1981).

Based on foraminifers, division 2682-3292 m may correlate approximately with the section spanning the Kugmallit Formation in the Richards Island area. The Kugmallit, although predominantly barren of foraminifers, yielded an Oligocene assemblage from its uppermost beds and an assemblage dated Eocene from its lower beds (Young and McNeil, in press).

Division 3292-3810 m (10 800-12 500 ft)

Division 3292-3810 m is characterized by a continuation of most of the common species of the overlying division and distinguished by **Haplophragmoides subtrullisatus** (Grzybowski), **Trochammina altiformis** Cushman and Renz, and **Gravellina** sp. (Plates 1, 3), as well as several other rare species restricted to this division (Fig. 7). Rare occurrences of calcareous benthic foraminifers in division 3292-3810 m are probably due to caved well-cuttings. The occurrence of **A. (R.) amplectens** throughout this division dates it within the Eocene.

Foraminifers are most abundant in a zone between 3231 and 3353 m (10 600 and 11 000 ft), straddling the upper divisional boundary and suggesting conformity between the two divisions. The zone corresponds closely to the lower unit of seismic sequence 4, a mudstone-rich unit interpreted as a basin plain to base-of-slope depositional unit. This relatively sandstone-free facies either supported an abundant foraminiferal population, or perhaps had a slower sedimentation rate, leading to an enrichment of foraminiferal tests. There is a notable decrease in the abundance of foraminifers below 3353 m (11 000 ft).

Several features of the assemblage are noteworthy. **Recurvoides** cf. **R. contortus,** a rotund **Recurvoides,** common in the overlying division, disappears, or is recorded only rarely, between 3292 and 3810 m. **Recurvoides** cf. **R. turbinatus** ranges through both divisions, but becomes flatter lower in the section, and closely resembles a species of **Recurvoides** characteristic of the Eocene Richards Formation in the Mackenzie Delta (Young and McNeil, in press). A 61 m thick zone near the top of the division is distinguished by **Gravellina** sp. **Gravellina** sp. has been noted in several other wells under the Beaufort Sea and appears to be a consistent stratigraphic marker, within the Middle or Late Eocene. The occurrence of this zone, a hundred metres or so above the oil-bearing sands at 3496 m (11 470 ft), lends it obvious importance for correlation.

Biostratigraphic comparison of division 3292-3810 m, southward toward the Richards Island area of the Mackenzie Delta, reveals only partial similarity with the upper part of the Richards Formation as described by Young and McNeil (in press). The correlation is tenuous due to a considerable biofacies change between the deep-water section at Kopanoar and the shelf section studied in the Richards Island area of the Mackenzie Delta. Only a few of the species, such as **Recurvoides** cf. **R. turbinatus,** are common between the areas. Distinctive Richards Formation species, such as **Alveolophragmium (R.)** sp. and **Jadammina** sp. of Young and McNeil (in press), are absent in the Kopanoar assemblage.

Division 3810-4320 m (12 500-14 172 ft)

Few foraminifers were recovered from division 3810-4320 m, and most of these probably result from caved well-cuttings. The upper boundary of the division is drawn arbitrarily below the last abundant occurrence of **Recurvoides** cf. **R. turbinatus.** Paleontological evidence is meagre and inconclusive for division 3810-4320 m, but an Eocene age is tentatively applied, based on seismic correlation with established Eocene sections elsewhere in the basin.

PALYNOMORPHS (J.P. Bujak and E.H. Davies)

Introduction

Two approaches proved particularly useful in the examination of the palynomorphs from the Kopanoar M-13 well. The first was the application of epifluorescence as a technique for distinguishing reworked palynomorphs, which constitute more than 95 per cent of the assemblage in the Late Miocene to Pleistocene section of the well. The second involved a comparison of the Beaufort Sea material with documented Neogene dinoflagellate assemblages from Deep Sea Drilling Project sites in the North Atlantic and North Pacific. It was possible to recognize Miocene dinoflagellate suites in the Beaufort Sea-Mackenzie Delta area. The potential value of these suites may have been previously overlooked since the Neogene has been a much neglected area of dinoflagellate study. Nonetheless, research published on Deep Sea Drilling Project (D.S.D.P.) cores by Costa and Downie (1979), Habib (1972), Harland (1979), Manum (1976), and Williams (1978), indicates an excellent potential for biostratigraphic refinement based on Neogene dinoflagellates.

Previous Beaufort Sea - Mackenzie Delta Cenozoic zonations

A formal zonation has not yet been proposed for the Beaufort Sea and Mackenzie Delta Cenozoic. Several papers, however, present preliminary biostratigraphic zonations. Staplin (1976) edited a biostratigraphic compilation by Gulf Oil Canada, Imperial Oil Limited and Mobil Oil Canada. Four informal zones were proposed for the Tertiary, three in the Paleogene and one, Zone T-4, in the Neogene. Zone T-4 was defined by the presence of **Sigmopolis** spp., an unnamed hyaline dinoflagellate cyst, and spores and pollen of a cool-temperate to boreal aspect.

Doerenkamp et al. (1976) erected an informal zonation for Cretaceous-Tertiary sediments on Banks Island and adjacent areas, including the Caribou Hills on the east side of the Mackenzie Delta. Ioannides and McIntyre (1980) also examined the Caribou Hills section, reporting on Late Cretaceous to Early Tertiary palynomorph assemblages.

Norris (in press) erected eight palynological zones for the Middle Eocene to Pliocene of the Imperial Nuktak C-22 well of the outer Mackenzie Delta. Except for one species, **Pyxidiella** sp. A, dinoflagellates were absent from the Neogene zones and only occurred in the Middle Eocene **Pesavis** Zone. The zone of particular relevance to the presence study is Norris's **Chenopodipollis** Zone, to which he assigned a Late Miocene or Pliocene age. The significance of this zone is discussed later in this paper.

In the Beaufort Sea, palynological and foraminiferal distributions for the Dome Gulf et al. Ukalerk C-50 well were presented by McNeil et al. (1982). They recognized a Late Oligocene to Pleistocene succession and presented preliminary biostratigraphic divisions for the well.

In conjunction with the current Kopanoar M-13 study, a geologic note on the Neogene dinoflagellate cysts in the Kopanoar M-13 well was presented by Bujak and Davies (1981).

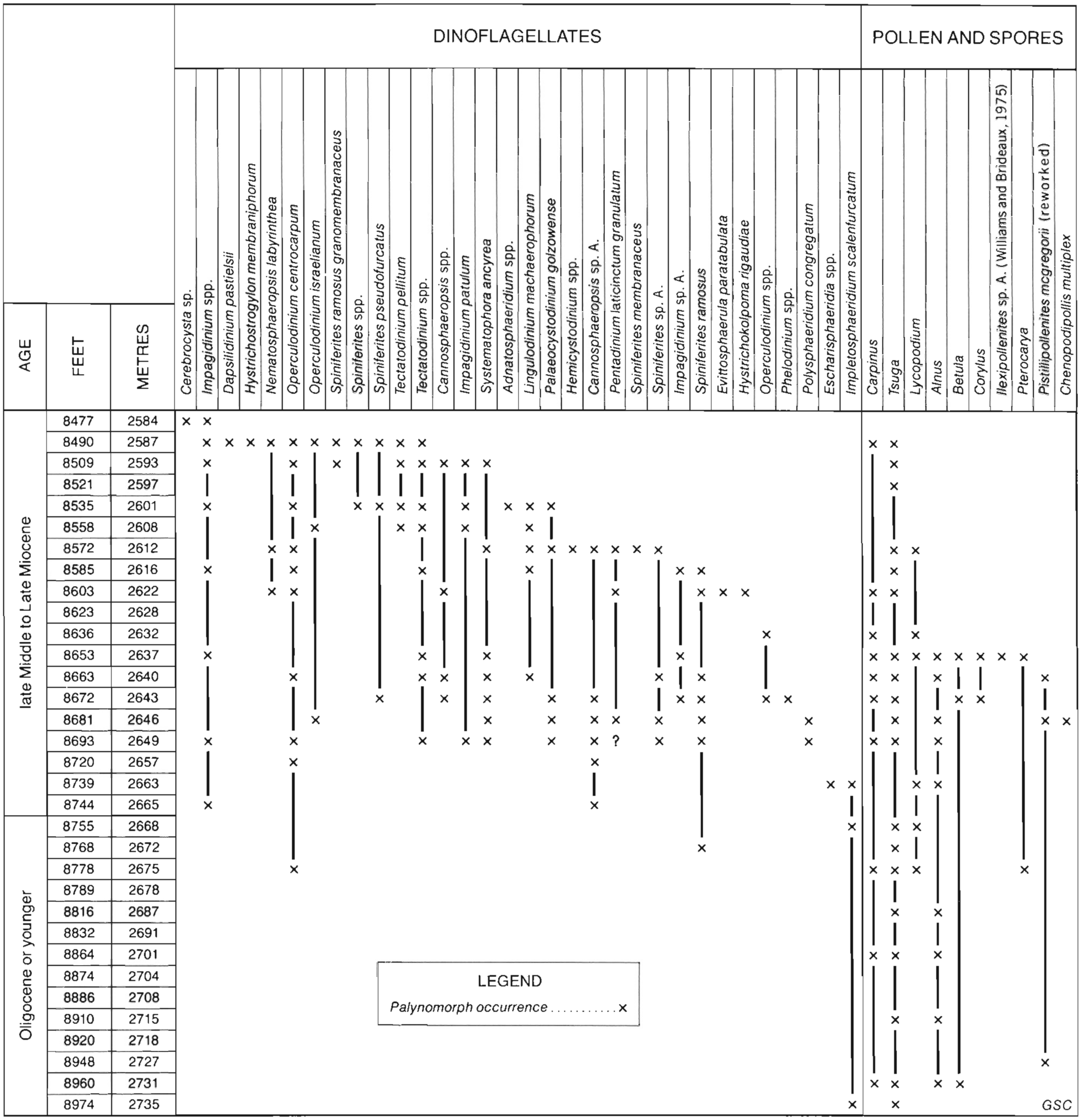

Figure 8. *Distribution of palynomorphs in sidewall cores between 2583 and 2735 m (8477 and 8974 ft) in the Kopanoar M-13 well.*

The microfloral assemblages

The Kopanoar M-13 well consists of three broad palynological units (Fig. 3). Selected species are illustrated in Plates 4 to 6. The uppermost unit, down to 1707 m (5600 ft), contains abundant palynomorphs showing various degrees of oxidation, biodegradation, breakage and thermal alteration. Using transmitted light it is difficult, if not impossible, to distinguish the indigenous population. Epifluorescence, however, reveals that over 95 per cent of the population is reworked. The indigenous species emit short wavelength fluorescence (Plate 5), whereas the reworked ones do not. The indigenous taxa include: **Pediastrum**, a freshwater chlorophycean; **Tasmanites**, a prasinophycean genus allied to the modern **Pachysphaera;** coniferous pollen such as **Picea** and **Pinus;** a variety of sphaeromorphic and acanthomorphic acritarchs, which probably represent the cysts of chlorophycean and other algae; and several dinoflagellate species. The latter are particularly interesting. They are colourless and transparent, almost invisible in regular transmitted light and unrecognizable in phase contrast illumination, but under epifluorescence their morphology is clear. They include **Rottnestia amphicavata** Harland et al., described from Holocene sediments of the Beaufort Sea by Harland et al. (1980), and several freshwater species similar to forms described by Norris and McAndrews (1970) from Recent freshwater lake sediments at Minnesota, U.S.A. A Pleistocene-Holocene age is indicated for sediments down to about 610 m (2000 ft) and a Pliocene-Pleistocene age for strata between 610 and 1707 m (2000-5600 ft).

Reworked palynomorphs below 1707 m, although still common, are more easily recognized, since they are mainly Mesozoic and Paleogene species that can be distinguished taxonomically. *In situ* dinoflagellates below 1707 m indicate a Miocene age. Marine species, such as **Systematophora ancyrea** Cookson and Eisenack, provide the first downhole correlation with assemblages of lower latitudes, including the Labrador Shelf (Williams and Bujak, 1977).

Thirty-three sidewall cores taken between 2584 and 2735 m (8477 and 8974 ft) yielded a mixed assemblage of marine and nonmarine palynomorphs. Spores and pollen are abundant throughout and include **Alnus, Betula, Carpinus, Picea,** and **Tsuga.** Fungal spores occur sporadically.

Dinoflagellate cysts are particularly common in the sidewall cores between 2584 and 2665 m (8477 and 8744 ft) (Fig. 8), and include more than 30 species. Most of these species have not been previously described, but several have been illustrated and given informal names. The two most common species present are **Cannosphaeropsis** sp. A and **Nematosphaeropsis** sp. B. **Cannosphaeropsis** sp. A was originally recorded by Williams and Brideaux (1975) from the Miocene of the Grand Banks. It was subsequently illustrated as **Impletosphaeridium** sp. I by Manum (1976) from Upper Oligocene to Upper Miocene strata of the Norwegian Sea and by Costa and Downie (1979) from the Middle Oligocene to Upper Miocene of Rockall Plateau. **Nematosphaeropsis** sp. B was described from the Miocene of the Grand Banks by Williams and Brideaux (1975). It differs from **Nematosphaeropsis labyrinthea** (Ostenfeld) Reid in having both thread- and ribbon-like trabeculae connecting the processes distally, and is probably synonymous with **Cannosphaeropsis** sp. of Harland (1979) from the Miocene of the Bay of Biscay.

Several species present between 2584 and 2665 m in the Kopanoar well have only been previously observed in North Pacific-Bering Sea assemblages (J.P. Bujak, pers. obs.), and include **Impagidinium** sp. A and **Spiniferites** sp. A. Species that are common in the Atlantic, but are rare in the North Pacific area, include **Cannosphaeropsis** sp. A of Williams and Brideaux, 1975, and **Nematosphaeropsis labyrinthea** (Ostenfeld) Reid. The closely allied species, **Nematosphaeropsis** sp. B of Williams and Brideaux, 1975, which is abundant in the North Pacific-Bering Sea area, is also common in the well. Also present is a particularly distinctive species, **Evittosphaerula paratabulata** Manum, previously known only from the Norwegian Sea (Manum, 1976) and almost certainly a cold water dinoflagellate taxon. Warmer water species, such as **Polysphaeridium zoharyi** (Rossignol) Bujak et al., are notably absent. The Beaufort Sea dinoflagellate assemblages thus appear to be intermediate in composition between those from the North Atlantic and North Pacific-Bering Sea areas.

The assemblages between 2584 and 2665 m indicate an age within nannoplankton zones NN7 to NN11, and planktonic foraminiferal zones N13 to N17 (late Middle-Late Miocene). This age determination is based on comparison with D.S.D.P. cores, which have ages established by fossil microplankton. This includes the work of Costa and Downie (1979) for the Rockall Plateau, Habib (1972) for the Hatteras Abyssal Plain, Harland (1979) for the Bay of Biscay, Manum (1976) for the Norwegian Sea, and personal observations of J.P. Bujak for the North Atlantic and North Pacific-Bering Sea area.

In addition to the dinoflagellates discussed above, the lowest occurrence of **Chenopodipollis** spp. was found in the sidewall core at 2646 m (8681 ft). This would correspond to the base of the **Chenopodipollis** zone (Norris, in press), which is characterized by the presence of **Chenopodipollis.** A Late Miocene to Pliocene age was assigned to this zone. The earliest occurrence of **Chenopodipollis** on the Grand Banks (Williams and Brideaux, 1975) occurs in the Miocene IV zone (Late Miocene). The presence of late Middle to Late Miocene dinoflagellates in the Kopanoar well supports the Late Miocene age assignment of the **Chenopodipollis** zone by Norris.

In the third portion of the well, below 2665 m (8744 ft), there is a marked decrease in dinoflagellate abundance and diversity. The pollen and spore floras are essentially the same as those above, but there is a progressive decrease in abundance and diversity downward, perhaps reflecting a change in proportions, caused by the diluting influx of tracheids, cuticle and other herbaceous matter. The consistent presence of **Tsuga igniculus** (Potonié) Potonié and Venitz in the sidewall cores down to 3542 m (11 620 ft), and in the cutting samples immediately below the casing point at 3680 m (12 074 ft), and continuing down to 4285 m (14 060 ft), indicates an Oligocene (or perhaps Late Eocene) or younger age. This interval would be equivalent to Zone T-3 (Staplin, 1976) in the Mackenzie Delta, or Eocene IV-Oligocene I of the Grand Banks (Williams and Brideaux, 1975). There is no strong palynological evidence to suggest an age older than Late Eocene for strata in the lower portion of the well.

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PLATES

1 - 6

PLATE 1

Figures

1. **Bathysiphon cylindrica** (Glaesner), x 14,
GSC 68727 from 3054 m below K.B.

2. **Bathysiphon nodosariaformis** Subbotina, x 17,
GSC 68728 from 3039 m below K.B.

3. **Bathysiphon nodosariaformis** Subbotina, x 25,
GSC 68729 from 3054 m below K.B.

4. **Bathysiphon pseudoloculus** (Myatliuk), x 38,
GSC 68730 from 3618 m below K.B.

5. **Bathysiphon pseudoloculus** (Myatliuk), x 46,
GSC 68731 from 3618 m below K.B.

6. **Jaculella acuta** Brady, x 20,
GSC 68732 from 3115 m below K.B.

7. **Psammosphaera fusca** Schulze, x 49,
GSC 68733 from 3679 m below K.B.

8. **Ammodiscus** cf. **A. angustus** (Friedburg), x 73,
GSC 68734 from 3298 m below K.B.

9a, b. **Reophax** sp., x 18,
GSC 68735 from 3557 m below K.B.

10. **Reophax nodulosus** Brady, x 30,
GSC 68736 from 3557 m below K.B.

11. **Reophax** cf. **R. nodulosus** Brady, x 25,
GSC 68737 from 3100 m below K.B.

12a, b. **Saccamminoides** (?) sp., x 37,
GSC 68738 from 3115 m below K.B.

13a, b. **Saccamminoides** (?) sp., x 36,
GSC 68739 from 3115 m below K.B.

14a-c. **Rzehakina epigona** (Rzehak), x 57,
GSC 68740 from 3374 m below K.B.

15a, b. **Rzehakina** (?) sp., x 49,
GSC 68741 from 3374 m below K.B.

16a, b. **Haplophragmoides** cf. **H. carinatus** Cushman and Renz, x 91,
GSC 68742 from 3786 m below K.B.

17a, b. **Haplophragmoides** cf. **H. rotulatum** (Brady), x 85,
GSC 68744 from 3572 m below K.B.

18a-c. **Haplophragmoides** cf. **H. carinatus** Cushman and Renz, x 61,
GSC 68743 from 3572 m below K.B.

19a-c. **Haplophragmoides subtrullisatus** Grzybowski, x 97,
GSC 68745 from 3694 m below K.B.

20a, b. **Haplophragmoides canariensis** (d'Orbigny), x 57,
GSC 68746 from 3679 m below K.B.

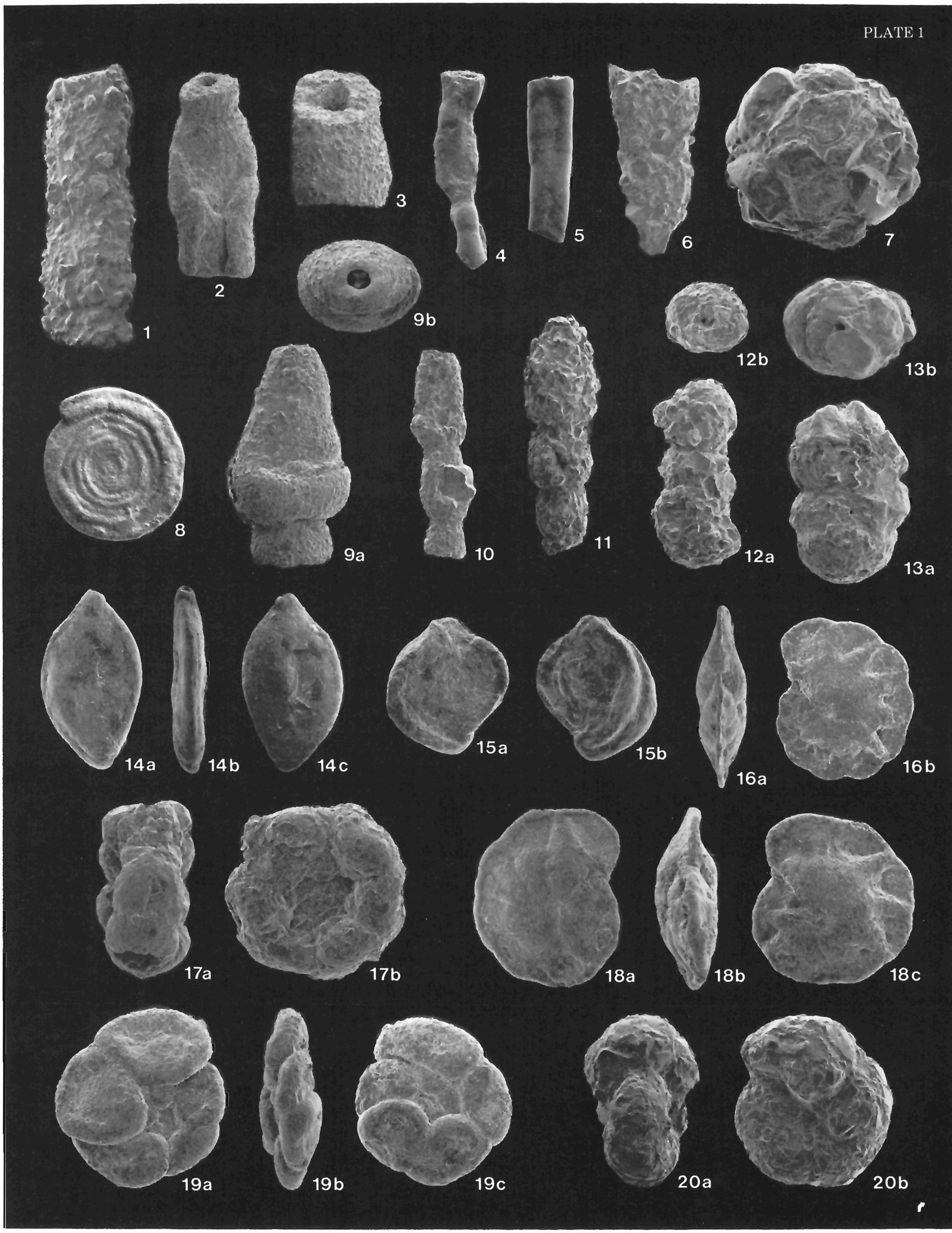
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PLATE 2

Figures

1a-c.	**Recurvoides** cf. **R. contortus** Earland, x 41, GSC 68747 from 3100 m below K.B.
2a-c.	**Recurvoides** cf. **R. contortus** Earland, x 42, GSC 68748 from 3255 m below K.B.
3a-c.	**Recurvoides** cf. **R. turbinatus** (Brady), x 49, GSC 68749 from 3648 m below K.B.
4a-c.	**Recurvoides** cf. **R. turbinatus** (Brady), x 70, GSC 68750 from 3664 m below K.B.
5a-c.	**Recurvoides trochamminiforme** Hoeglund, x 60, GSC 68751 from 3039 m below K.B.
6a-c.	**Alveolophragmium (Reticulophragmium) amplectens** (Grzybowski), x 57, GSC 68752 from 3133 m below K.B.
7a, b.	**Alveolophragmium (Reticulophragmium) rotundidorsata** (Hantken), x 46, GSC 68753 from 3054 m below K.B.
8a, b.	**Alveolophragmium (Reticulophragmium) rotundidorsata** (Hantken), x 36, GSC 68754 from 3255 m below K.B.

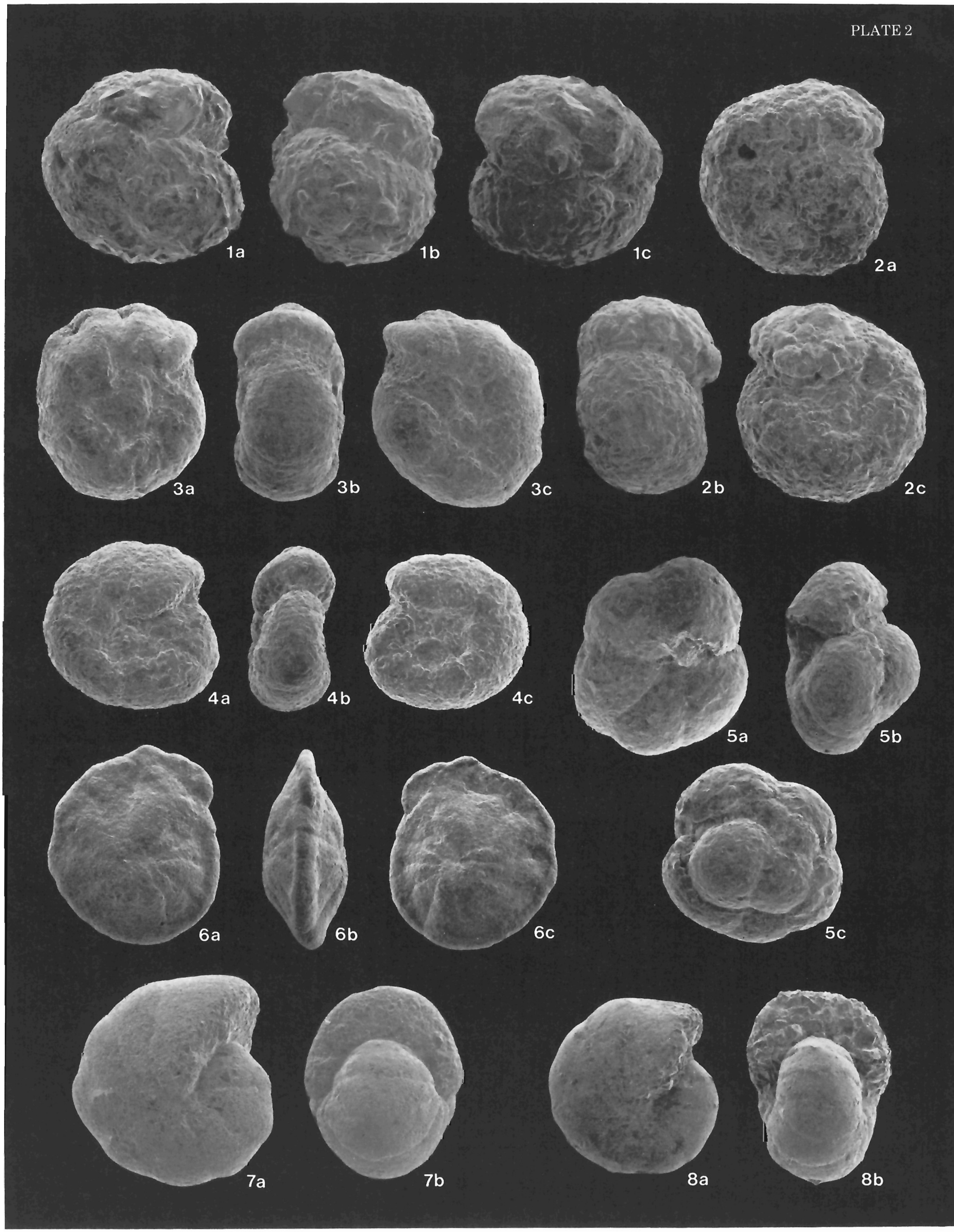
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PLATE 3

Figures

1a, b.	**Alveolophragmium (Reticulophragmium)** sp. 1, x 39, GSC 68755 from 3161 m below K.B.
2a, b.	**Alveolophragmium (Reticulophragmium)** sp. 1, x 35, GSC 68756 from 3084 m below K.B.
3a-c.	**Alveolophragmium (Reticulophragmium)** sp. 2, x 57, GSC 68757 from 3054 m below K.B.
4a, b.	**Alveolophragmium (Reticulophragmium)** sp. 2, x 50, GSC 68758 from 3328 m below K.B.
5a-c.	**Trochammina altiformis** Cushman and Renz, x 86, GSC 68759 from 3664 m below K.B.
6a-c.	**Trochammina altiformis** Cushman and Renz, x 110, GSC 68760 from 3344 m below K.B.
7a-c.	**Cystammina pauciloculata** (Brady), x 76, GSC 68761 from 3298 m below K.B.
8a-c.	**Trochammina subvesicularis** Homola and Hanzlikova, x 90, GSC 68762 from 3024 m below K.B.
9a, b.	**Gravellina** sp., x 48, GSC 68763 from 3344 m below K.B.

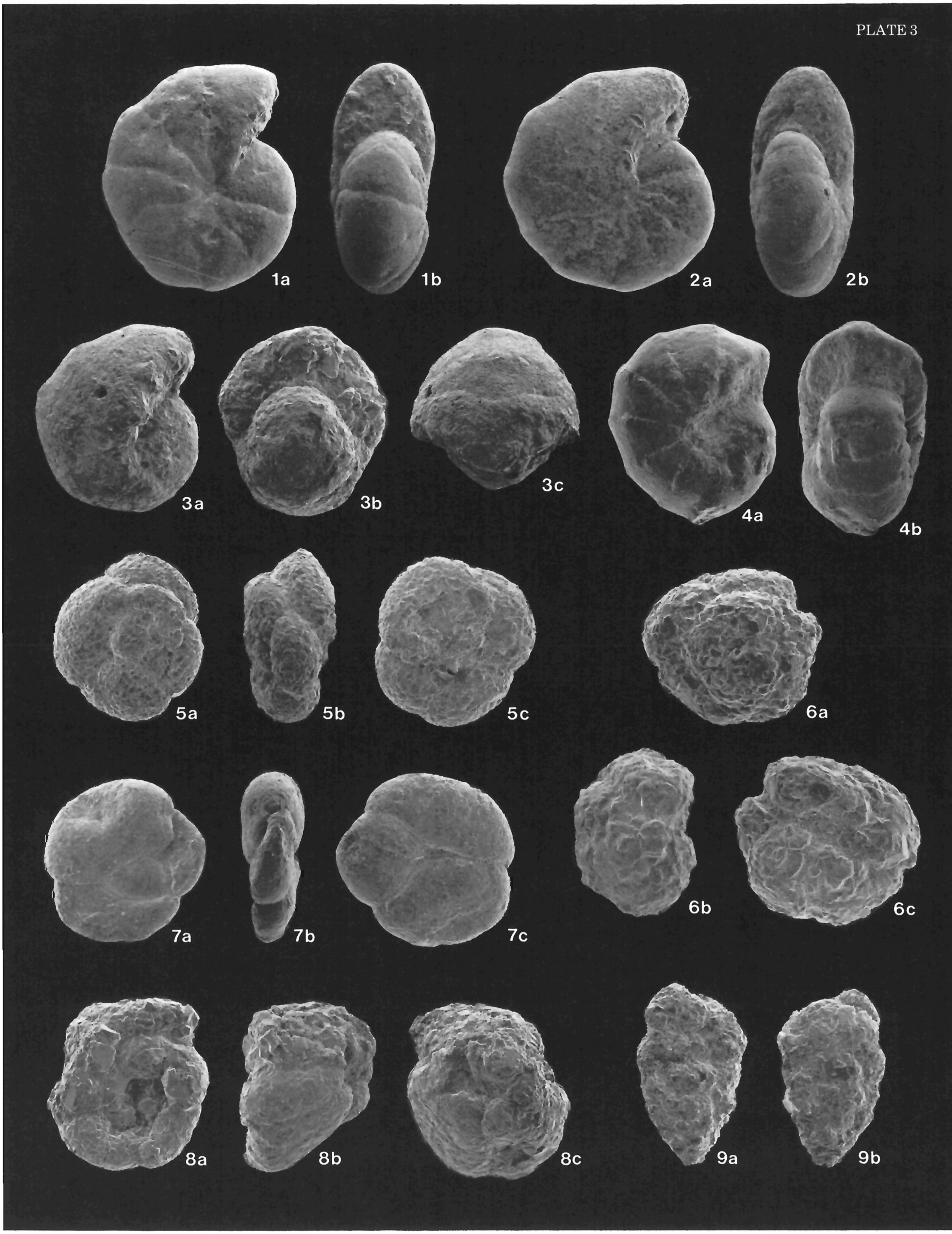
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PLATE 4

Figures

1. **Peridinium** cyst type D of Norris and McAndrews 1970. Slide P-2106-1, + 45 µm fraction; cutting sample, 488-515 m (1600-1690 ft); coordinates 10.8/96.4; GSC 68764.

2. **Brigantodinium** sp. Slide D005-77C; sidewall core 2749 m (9020 ft); coordinates 13.0/99.1; GSC 68765.

3. **Diconodinium multispinulum** (Deflandre and Cookson) Eisenack and Cookson, a reworked Cretaceous specimen. Slide D005-77C; sidewall core, 2749 m (9020 ft); coordinates 18.6/97.1; GSC 68766.

4. **Evittosphaerula paratabulata** Manum. Slide D005-175C; sidewall core, 2643 m (8672 ft); coordinates 06.2/105.0; GSC 65089.

5. **Impagidinium** sp. A. Specimen from D.S.D.P. Site 183, core 27, section 4 (67-71 cm); coordinates 06.4/87.9; Aleutian Abyssal Plain; specimen shows high, thin sutural crest typical of the species; GSC 65090.

6. **Spiniferites** sp. A. Slide D005-176C; sidewall core, 2646 m (8681 ft); coordinates 11.2/83.4; GSC 68767.

7. **Nematosphaeropsis** sp. B of Williams and Brideaux, 1975. Slide D005-175C; sidewall core, 2643 m (8672 ft); coordinates 19.6/94.0; GSC 65088.

8, 9. **Cannosphaeropsis** sp. A of Williams and Brideaux, 1975.

   8. Slide P-2106-71 Kerogen; cutting sample, 2621-2649 m (8600-8690 ft); coordinates 18.6/82.1; GSC 68768.

   9. Slide D005-175C; sidewall core, 2643 m (8672 ft); coordinates 11.2/92.0; GSC 68769.

10. **Nematosphaeropsis labyrinthea** (Ostenfeld) Reid. Slide D005-170C; sidewall core, 2622 m (8603 ft); coordinates 160/80.3; GSC 65087.

11. **Ilexipollenites** sp. A of Williams and Brideaux, 1975. Slide D005-173C; sidewall core, 2637 m (8653 ft); coordinates 13.7/94.4; GSC 68770.

12. **Chenopodipollis multiplex** Krutzsch. Slide D005-176C; sidewall core, 2646 m (8681 ft); coordinates 16.5/94.3; GSC 68771.

PLATE 4

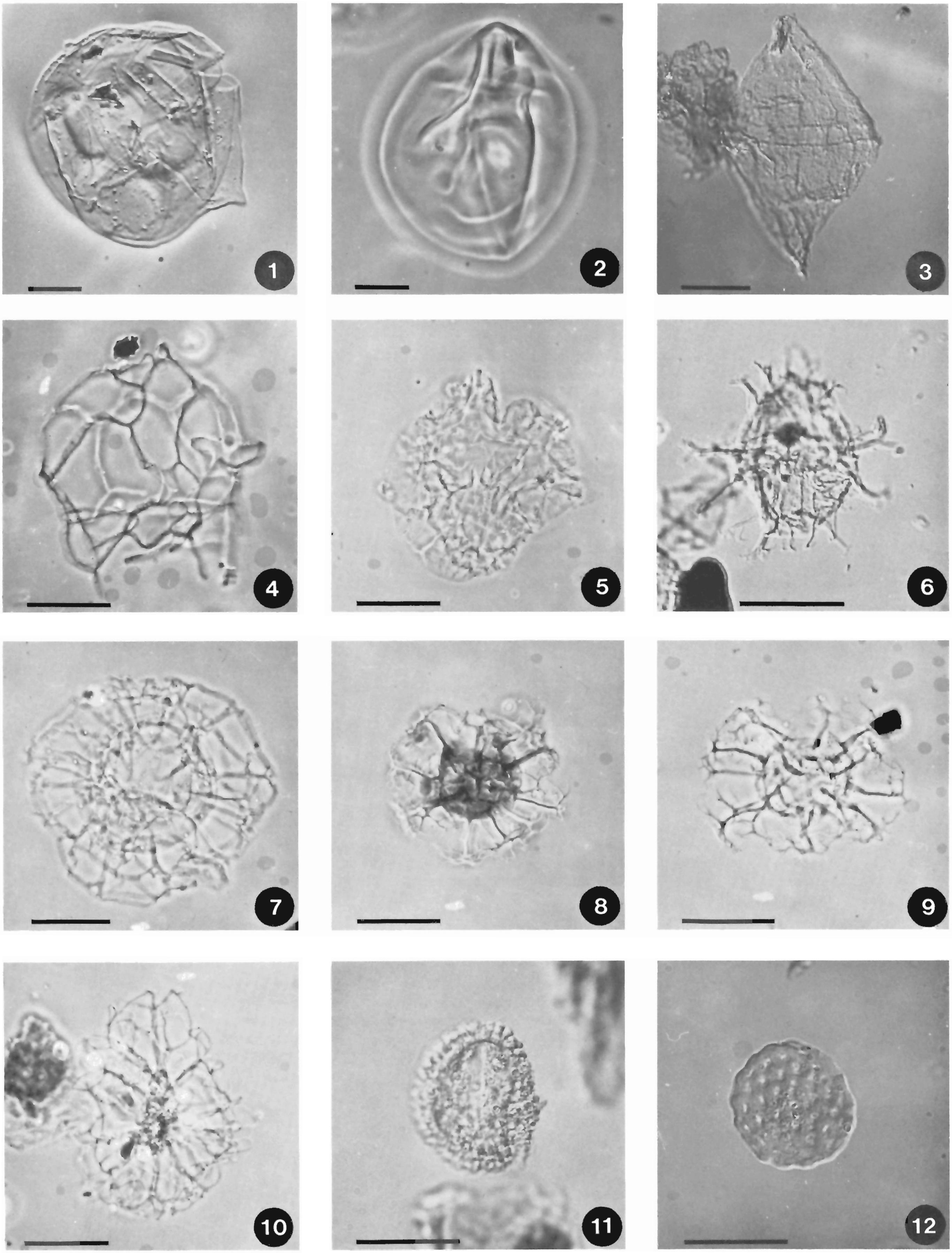

PLATE 5

NOTE: Specimens in figures 1 to 11 are observed through a Zeiss fluorescence filter set, allowing wavelengths greater than 520 nm to pass. The specimen from Figure 12 is observed through a filter set, allowing wavelengths of 418 to 420 nm to pass.

Figures

1. **Micrhystridium fragile.**
Slide P-2106-5 Kerogen; cutting sample, 610-637 m (2000-2090 ft); coordinates 150/1040; GSC 68772.

2. **Veryhachium** sp.
Slide P-2106-10 Kerogen; cutting sample, 762-789 m (2500-2590 ft); coordinates 08.6/109.1; GSC 68773.

3. **Pterospermella** sp.
Slide P-2106-5 Kerogen; cutting sample, 610-637 m (2000-2090 ft); coordinates 12.2/114.2; GSC 68774.

4. **Pediastrum** sp.
Slide P-2106-1 Kerogen; cutting sample, 488-515 m (2000-2090 ft); coordinates 13.6/107.8; GSC 68775.

5. Peridiniacean cyst.
Slide P-2106-5 Kerogen; cutting sample, 610-637 m (2000-2090 ft); coordinates 15.6/95.4; GSC 68776.

6. Peridiniacean cyst.
Slide P-2106-5 Kerogen; cutting sample, 610-637 m (2000-2090 ft); coordinates 12.8/101.0; GSC 68777.

7. **Rottnestia amphicavata** Harland et al.
Slide P-2106-5 Kerogen; cutting sample, 610-637 m (2000-2090 ft); coordinates 14.0/99.8; GSC 68778.

8. Peridiniacean cyst.
Slide P-2106-10, + 45 μm fraction; cutting sample, 762-789 m (2500-2590 ft); coordinates 08.4/97.4; GSC 68779.

9. Peridiniacean cyst.
Slide P-2106-35 Kerogen; cutting sample, 1524-1551 m (5000-5090 ft); coordinates 07.7/113.4; GSC 68780.

10. **Albies** pollen.
Slide P-2106-1 Kerogen; cutting sample, 488-515 m (1600-1690 ft); coordinates 08.0/104.8; GSC 68781.

11, 12. **Leiosphaera** sp. (Fig. 11, viewed through filter allowing wavelengths greater than 520 nm to pass; Fig. 12, viewed through filter allowing wavelengths between 418 and 420 nm). Slide P-2106-5 Kerogen; cutting sample, 610-637 m (2000-2090 ft); coordinates 113/104.1; GSC 68782.

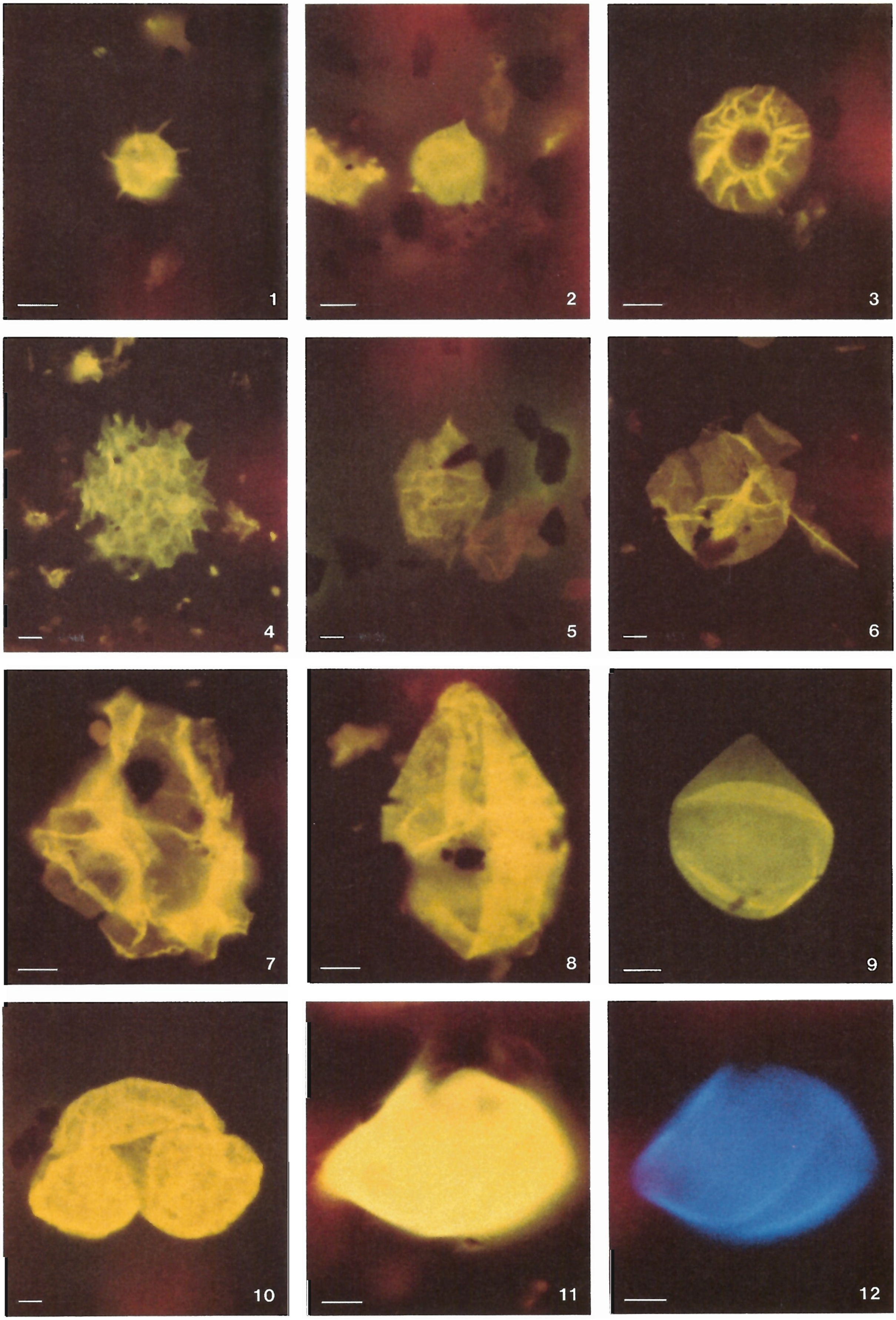
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PLATE 6

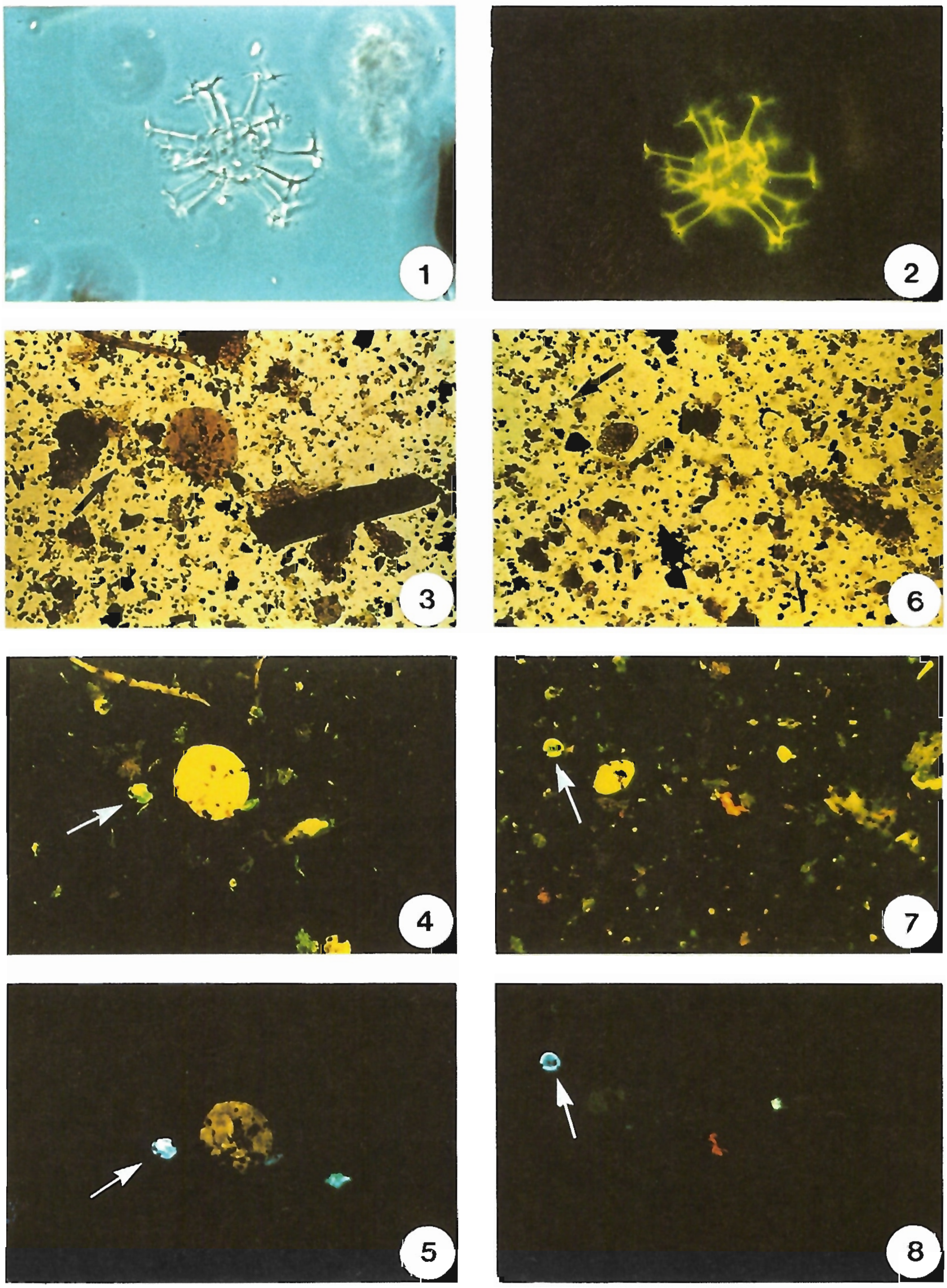
Figures

1, 2. **Cannosphaeropsis** sp. A of Williams and Brideaux (1975). Slide D005-168C, sidewall core, 2613 m (8572 ft); England Finder coordinates M28/2; GSC 68783.

1. Under transmitted light, phase contrast illumination.
2. Under fluorescence filter set, allowing wavelengths greater than 520 nm to pass. This specimen, of Miocene age, is probably in place and is emitting yellow fluorescence.

3-8. Views of kerogen sample under different optical systems. The arrows point to pollen grains that are probably in place and one barely visible under bright field transmitted light (figs. 3, 6). These are emitting yellow-green fluorescence under a fluorescence filter set allowing wavelengths greater than 520 nm to pass (figs. 4, 7), and are emitting blue fluorescence under a fluorescence filter set allowing wavelengths between 418 and 420 nm to pass (figs. 5, 8). Note the progressive loss of visible kerogen particles as the wavelengths become shorter in figures 4 and 7, and figures 5 and 8.

Slide P-2106-1; cutting sample, 488-515 m (1600-1690 ft).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ADDENDUM

Further research on the internal morphology of the alveolar-walled species from the Kopanoar M-13 borehole has proven that *Alveolophragmium* (*R.*) *amplectens* (Grzysbowski) was misidentified in this report and should be referred to as an unnamed species of *Alveolophragmium* (*R.*). The original identification was based on external morphology, but detailed examination of the internal alveolar structure of the Kopanoar M-13 material and of topotypes of *A.* (*R.*) *amplectens*, kindly provided to D.H. McNeil by Dr. S. Geroch of the Jagellonian University, Krakow, Poland, indicates that the Kopanoar specimens are of a different species.

The above misidentification considerably affects the age determinations for biostratigraphic divisions 2682-3292 m and 3292-3810 m. There is now little or no evidence that these two divisions are of Eocene age, and an Oligocene age probably applies.

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