# QUATERNARY DINOFLAGELLATE CYST BIOSTRATIGRAPHY OF THE NORTH SEA

## by REX HARLAND

ABSTRACT. The dinoflagellate cyst biostratigraphy of Quaternary sediments in the North Sea is described. The data accumulated demonstrate the recognition of glacial, interstadial, and interglacial periods but do not necessarily date the relevant sediments. Certain major events such as the distinctive change from the Early Pleistocene to Middle and Late Pleistocene conditions are particularly noted, as is the onset of the modern oceanographic situation, all of which have distinctive signals in the dinoflagellate cyst record. The potential for using dinoflagellate cysts in correlating shelf, slope, and ocean sediments is stressed.

THE Quaternary is characterized by climatic fluctuations that have served long as the basis for its subdivision. Indeed climatic fluctuation is accepted as the guiding principle for defining its various stages (Shotton 1973). Imbrie (1985) admits that even after 150 years of study no fully satisfactory theory exists to explain all climatic variations. Nonetheless it is now increasingly accepted that on a 10 000 to 400 000 year time-scale, variation in the Earth's orbit including eccentricity, obliquity, and precession is the fundamental cause of climatic fluctuations. At the smaller scale there is evidence that changes in solar activity, or episodes of volcanism may exert some influence.

Although the effects of climatic change may be quite differently recorded depending upon the geographic position of the recipient site the driving force is almost certainly planetary. Therefore the initiation of the various effects must be essentially isochronous even though the rate of response of the physical and biological system will be different, not least because of the many complex feedback systems that operate.

Historically the possibility of significant climatic change was first realized in the terrestrial environment from the recognition of glaciogenic sediments in areas not currently affected by glacial activity. More recently the marine record has come under increasingly closer scrutiny with the availability of ocean sediment cores and the techniques of oxygen isotope and palaeomagnetic analysis. Chemical (Arrhenius 1952), micropalaeontological (Ericson et al. 1956), and oxygen isotope analyses (Shackleton 1969) have given way to such integrated studies as the work of the CLIMAP (Cline and Hays 1976) and OSKAP (Stabell and Thiede 1985) projects. This approach has vastly improved the understanding of the nature, frequency, and effect of major climatic events in the marine Quaternary record (West 1985).

Despite these major advances based upon deep-ocean marine sediments relatively little is known of the contemporaneous continental shelves, which promise much in linking the deep ocean and terrestrial records. Some significant progress has been made in the North Atlantic area around the British Isles (Binns, Harland and Hughes 1974; Binns, McQuillin and Kenolty 1974; Caston 1977; Holmes 1977; Thomson and Eden 1977; Pantin 1978; Skinner and Gregory 1983; Stoker et al. 1983, 1985a, b; Davies et al. 1984), the Netherlands (Jansen 1976, 1980; Jansen et al. 1979), Norway (Feyling-Hanssen 1981, 1982; Knudsen 1985; Mangerud et al. 1984; Stabell and Thiede 1985), and Canada (Mudie and Aksu 1984; Scott et al. 1984; Aksu and Mudie 1985).

A major problem in Quaternary shelf sediment studies is the provision of a reliable biostratigraphy. Shotton (1973) points out that a biozonation based upon the appearance and extinction of species is impractical because the duration of the Quaternary is insufficient to encompass more than one or two biozones at most. In all groups the extant species are often dominant in Quaternary assemblages and so any biostratigraphical divisions are necessarily the result of interpreted environmental change

as exemplified by the changing sequential assemblages of pollen and Coleoptera (Moore and Webb 1978; Coope 1977).

Fossil groups used in the recognition of environment/climatic change within the marine realm include planktonic and benthonic Foraminifera, ostracodes, molluscs, coccoliths, and diatoms. However, of late, one group, the dinoflagellates, is becoming increasingly utilized. These marine planktonic algae (Division Pyrrhophyta), contain genera and species that produce hypnozygotic cysts resistant to bacterial decay and hence with fossilization potential. Dinoflagellate cysts in marine Quaternary sediments can be used to decipher environmental and climatic history (Dale 1983, 1985). Recent studies of such cysts have underlined their usefulness in the interpretation of the marine Quaternary record on land (Wall and Dale 1968a), on the continental shelf (Harland 1977), and in the deep ocean (Turon 1980). The potential for correlating the shelf with the deep ocean, a potential not shared by either planktonic Foraminifera or coccolithophores, has not yet been fully realized (Harland 1984c; Bakken and Dale 1986), nor has their use in charting climatic of oceanographic change throughout the marine realm.

The present paper attempts to document the Quaternary dinoflagellate cyst biostratigraphy for the North Sea area and to relate it where possible to oceanographic fluctuations in the North Atlantic Ocean and to climate change in the Northern Hemisphere. It is based on studies at the British Geological Survey (BGS) for the Marine Earth Sciences Research Programme and the East Anglian Regional Mapping Programme and centres around the central North Sea. Other work includes recent analyses of sediment cores from the outer continental shelf and the continental slope of the north-west of the British Isles, and to work published on DSDP Legs 80 and 81 (Harland 1984a, b).

## MATERIAL AND METHODS

The study samples, collated from vibrocores and boreholes drilled as part of the BGS exploration of eastern England and the continental shelf, are of clay, silt, or fine sand; finer grade material being preferred over coarse because dinoflagellate cysts tend to act as sedimentary particles of fine silt size (Dale 1976). Details of the vibrocores and boreholes may be found in BGS registers at Keyworth and Edinburgh and many are described in the Institute of Geological Sciences (1974 et seq.) and British Geological Survey (1984 et seq.).

All the samples are cleaned and only those portions thought free of outside contamination were processed. Normal palynological processing was used throughout but the samples were subjected to the sintered glass funnel technique of Neves and Dale (1963) for washing, concentrating, and staining. No oxidizing method was used, if at all possible, in an attempt to reduce the loss of the more susceptible peridiniacean cysts (Dale 1976). Strew slides were made by dispersing the microfossils on coverslips and then mounting in Elvacite.

As a general rule a single slide per sample was counted for its dinoflagellate cyst content and to give the proportions of the various species. Although the technique was standardized as far as possible to yield consistent results, at this reconnaissance level the results can only be semi-quantitative at best. Rich and diverse samples were counted to give a minimum of some 100 specimens for any one particular species. This method has proved sufficient, in samples that contain widely different numbers of cysts, to recognize patterns of fluctuation. Such counts for the majority of samples where less than twenty species are present give cyst proportions with errors between 3 % and 9 % of the estimated percentages at two standard deviations, depending upon numbers of specimens counted (Van der Plas and Tobi 1965).

The dinoflagellate cyst spectra illustrate the proportions of the various genera and/or species together with the numbers counted. The number of counted cysts per slide is also a useful, if limited, 'rule of thumb' guide to the richness of the samples.

Although the methodology outlined above is not statistically rigorous the patterns of dinoflagellate cyst fluctuations and climatic change are thought to be real. They have largely been confirmed by the study of other fossil groups, e.g. benthonic Foraminifera, and by other geological techniques.

All the slides, records, and illustrated specimens are housed in the palynological collections of the BGS at Keyworth.

## INTERPRETATION OF THE DINOFLAGELLATE CYST RECORD

The dinoflagellate cyst analysis of continental shelf sediments has used various interpretative methods. Some of the earlier work relied heavily upon the recognition of sedimentary units favourable or unfavourable for dinoflagellate cysts which were largely equated with climatic ameliorations (interglacials or interstadials) and deteriorations (glacials) respectively.

This led to the documentation of various climatic sequences and attempts at correlation (Harland 1973, Harland 1974, Binns, Harland and Hughes 1974 and Hughes et al. 1977) but suffered from difficulties in the recognition of changes in dinoflagellate richness, because of lithological variations, and lacked precision in the use of syn- and autecological data from the study of modern dinoflagellates and their cysts.

The method was later supplemented by limited ecological data as it became available. Nonetheless sequences were described in terms of patterns of favourability and unfavourability, plus the growing recognition that certain dinoflagellate cyst species were important in imparting specific ecological information, especially in respect of changes in water mass and hence the influence of the North Atlantic Current (Harland 1977; Harland et al. 1978; Gregory and Harland 1978).

More recently work on sequences recovered from the Deep Sea Drilling Project (Harland 1979, 1984a, b), on dinoflagellate cyst thanatocoenoses (Reid 1975; Reid and Harland 1977; Wall et al. 1977; Turon 1980; Harland 1983; Bradford and Wall 1984; Mudie and Short 1985; Matsuoka 1985b), and from living dinoflagellate cysts (Dale 1976, 1983, 1985; Balch et al. 1983; Lewis et al. 1984) has produced a growing volume of relevant data greatly assisting the understanding of the ecological requirements of many dinoflagellates

It has also become possible to examine the contained dinoflagellate cyst assemblage, whether rich or poor, in terms of species presence alone and interpreted from a knowledge of dinoflagellate ecology. The literature now contains sequences for which diagrams have been drawn showing the changing relative frequencies of cysts present (Turon 1980; Harland 1982; Cameron et al. 1984; Harland 1984 a, b, c; Scott et al. 1984; Dale 1985; Long et al. 1986). Thus dinoflagellate cyst spectra have begun to be constructed for marine Quaternary sequences in the same way as pollen spectra have been drawn for continental sequences.

Here sequences are categorized by their dinoflagellate cyst content, and diagrams are drawn to illustrate the cyst assemblages for the various seismostratigraphic units. Units of rich dinoflagellate cyst occurrence are easily recognizable and interpreted using autecological data.

Especially important, in the context of changing climatic environments, is the recognition of the influence of Atlantic water, i.e. north-temperate and normally saline waters with rich and diverse associations of Operculodinium centrocarpum (Deflandre and Cookson) Wall, Nematosphaeropsis labyrinthea (Ostenfeld) Reid, Spiniferites membranaceus (Rossignol) Sarjeant, S. mirabilis (Rossignol) Sarjeant, and S. ramosus (Ehrenberg) Loeblich and Loeblich, together with some Protoperidinium species such as P. conicum (Gran) Balech, P. leonis (Pavillard) Balech, and P. pentagonum (Gran) Balech; and more Arctic water with poorer and less diverse associations of Bitectatodinium tepikiense Wilson, elongate Spiniferites spp., and such round brown Protoperidinium spp. as P. conicoides (Paulsen) Balech. Transitional situations also exist and often the assemblage sequences are complex with proportions of cysts not well known from modern environments.

The dinoflagellate associations reflect the same kind of changing environment as those that have been documented by the CLIMAP project (Cline and Hays 1976; Ruddimann and McIntyre 1981) using other fossil groups. Although they have not been applied in sufficient detail to test the precision and sensitivity of the group, patterns of climatic change are most definitely reflected in the dinoflagellate cyst assemblages.

Finally the interpretation of the cyst record has been somewhat complicated by problems in rationalizing two systems of taxonomy, originating because of the separate study of living motile dinoflagellates by phycologists, and the study of cysts by palaeo-palynologists. The use of incubation experiments (Wall and Dale 1968b) and more recently by Matsuoka (1984, 1985a), Matsuoka et al. (1982), and Lewis et al. (1984) has allowed some integration of systems (Harland 1982), but not

without controversy (Dale 1983). At present several procedures are used which include the use of the fossil nomenclature, modern biological nomenclature, and an amalgamation of the two systems. This reflects our present knowledge but more particularly is an honest attempt to use the maximum amount of information inferred by the use of any particular name.

## STRATIGRAPHY

*Introduction*

Stoker *et al.* (1985*a*, *b*) presented a stratigraphic framework for Quaternary sediments in the central part of the North Sea following the earlier works of Holmes (1977) and Thomson and Eden (1977). Their synthesis
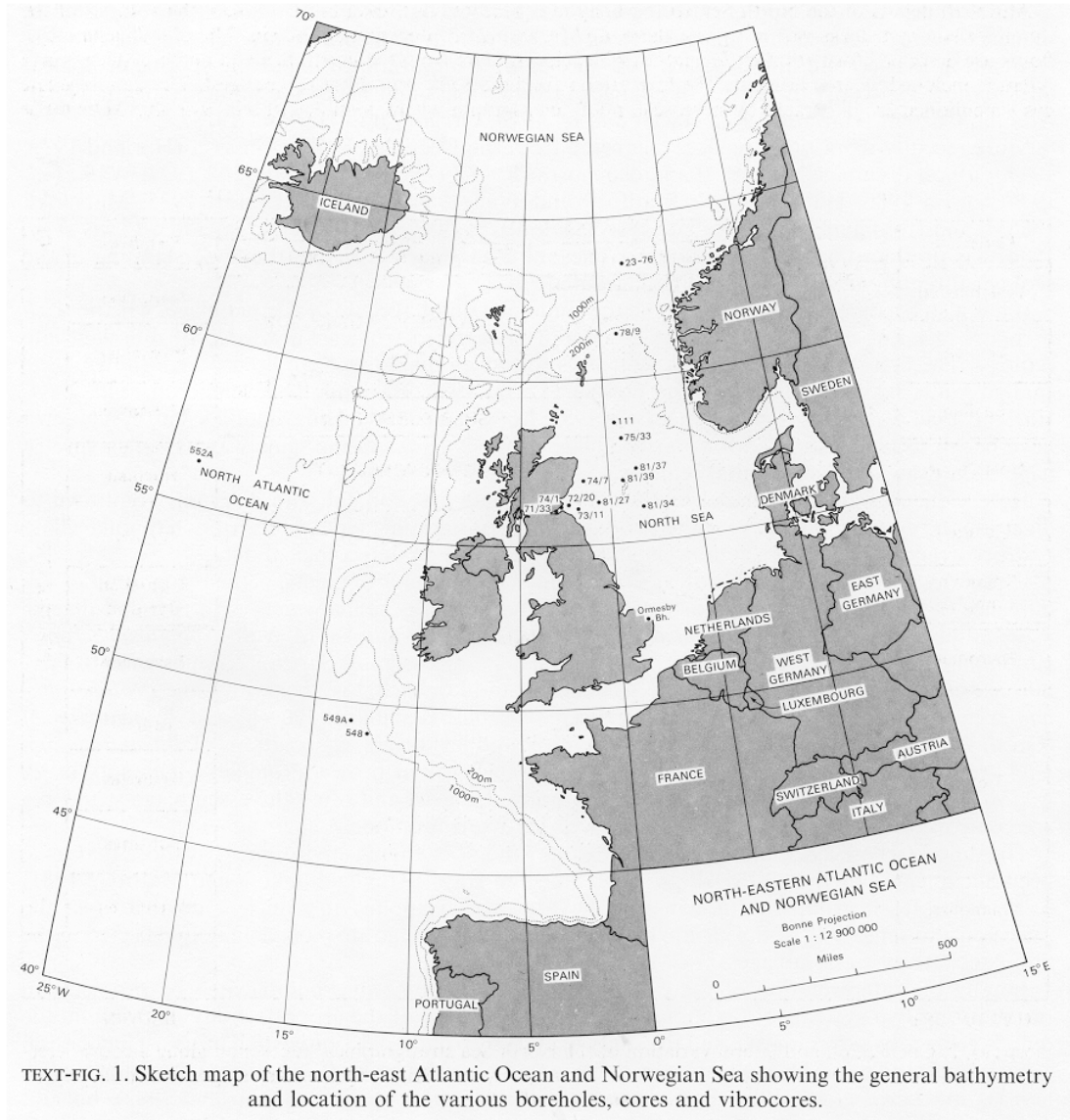


TEXT-FIG. 1. Sketch map of the north-east Atlantic Ocean and Norwegian Sea showing the general bathymetry and location of the various boreholes, cores and vibrocores.

is based upon a seismostratigraphic approach but includes lithological, geotechnical, palaeomagnetic, and micropalaeontological data including the analysis of dinoflagellate cysts.

Ten major Quaternary formations were formally recognized by Stoker et al. (1985b) that individually can reach some 200 m in thickness. The base of the oldest Quaternary formation was not observed or sampled and indeed the actual base of the Quaternary itself cannot be identified with any certainty.

In Britain the base of the Quaternary has been taken at the base of the Waltonian Red Crag (Shotton 1973) or perhaps better termed the Pre-Ludhamian (Beck et al. 1972). However, Funnell in Curry et al. (1978) argues that the Waltonian should be regarded as a part of the Pliocene such that the Plio/Pleistocene boundary must lay somewhere within or above the Red Crag. Berggren et al. (1985) report a resolution to the IUGS recommending the boundary be taken at the top of marker bed e at about 3–6 m above the Olduvai normal polarity event within the Matuyama reversed epoch at the Le Castella Section. This is at 1·6 My and commonly used as the boundary in the central part of the North Sea.

Although details of the North Sea stratigraphy are presented in Stoker et al. (1985b) the analysis of the dinoflagellate cyst floras was not given there, and hence will be documented herein. The dinoflagellate cyst floras are described formation by formation with relevant data from the North Sea and north-eastern North Atlantic included where pertinent. The formations are discussed from oldest to youngest. The dinoflagellate cysts mentioned are illustrated by stereoscan photomicrographs where possible but reference should be made
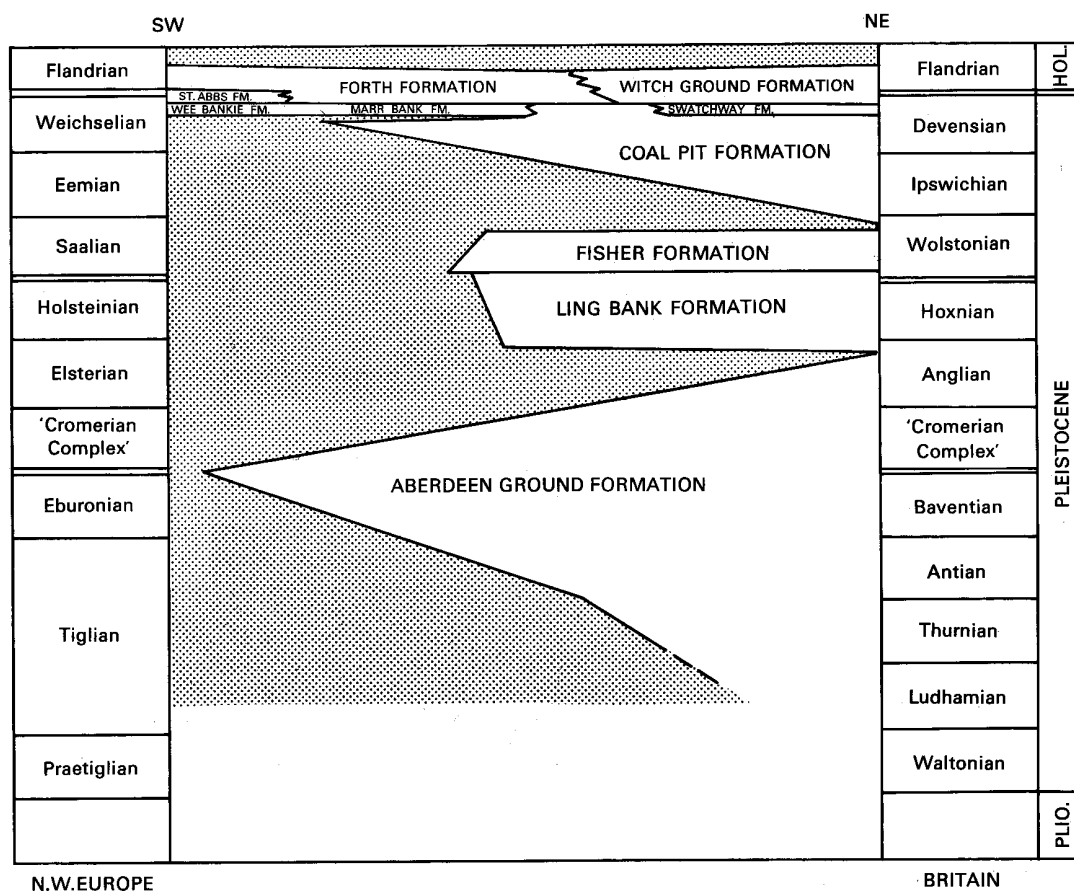


TEXT-FIG. 2. Correlation and lateral variation of the North Sea stratigraphical succession along a south-west–north-east transect in relation to the north-west European and British Quaternary stages (based largely on Stoker et al. 1985b).
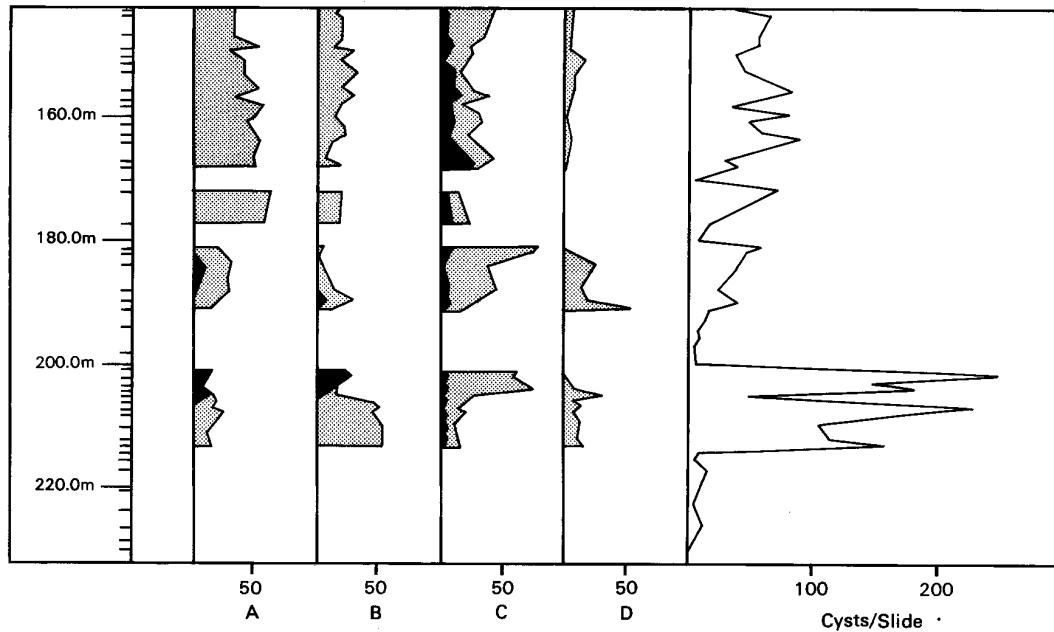
TEXT-FIG. 3. Dinoflagellate cyst biostratigraphy of the Aberdeen Ground Formation in Borehole 81/34, lat. 56° 7·68′ N., long. 1° 35·21′ E. A, *Operculodinium centrocarpum* (Deflandre and Cookson) Wall with *O. israelianum* (Rossignol) indicated in black. B, *Bitectatodinium tepikiense* Wilson with *Tectatodinium pellitum* Wall indicated in black. C, *Spiniferites* cysts with *Achomosphaera andalousiensis* Jan du Chêne in black. D, *Protoperidinium* cysts. Small ticks in first column indicate sample levels.

to Harland (1977, 1983) for the taxonomy and to Dale (1983) and Harland (1983) for the ecology and cyst distributions respectively.

### Aberdeen Ground Formation

The type sequence occurs in Borehole 81/34 between 142.0 and 229.1 m, but unfortunately the borehole did not prove the base. The location of Borehole 81/34 and all subsequent cores are shown in text-fig. 1. The interpreted sequence and lateral variations are illustrated in text-fig. 2. The Aberdeen Ground Formation consists of dark-grey to brown, very stiff to hard silty muds with some shelly and pebbly sands. Stoker *et al.* (1983) have identified the Brunhes/Matuyama palaeomagnetic boundary within the formation, and have indicated a Tiglian to 'Cromerian Complex' (late Antian to Cromerian) age (Early to Middle Pleistocene).

The dinoflagellate cyst spectrum for the Aberdeen Ground Formation in Borehole 81/34 is given in text-fig. 3. It is immediately apparent that samples between 200 m and 214 m yielded rich dinoflagellate cyst assemblages in contrast to the remainder of the section. This suggests that only during this time were conditions favourable enough to allow a relative rise in the recruitment (no. of cysts per gram of sediment being incorporated at any particular time) of the dinoflagellate cysts. During this interval two distinct episodes are recognized. There is an older period dominated by *B. tepikiense* (*c.* 50%) (text-fig. 4) and a younger dominated by *Spiniferites* spp. (*c.* 60 %) (Pl. 79, figs. 1-6). The cyst *Achomosphaera andalousiensis* Jan du Chêne (Pl. 81, figs. 1-4) is consistently present throughout the sequence. Although environmental conditions may be favourable, the presence of high proportions of *B. tepikiense* and the persistence of *A. andalousiensis* suggest rather cold, north-temperate to arctic-like environments. *B. tepikiense* is well known as a north-temperate cyst (Harland 1983; Dale 1983) and although *A. andalousiensis* has rarely been recovered from modern sediments (Harland 1983; Balch *et al.* 1983), it has been associated with cold north-temperate to arctic environments (Long *et al.* 1986). The upper part of this section with higher proportions of *Spiniferites* spp., but not *A. andalousiensis*, and with lower proportions of *B. tepikiense* may indicate the maximum occurrence of the amelioration.
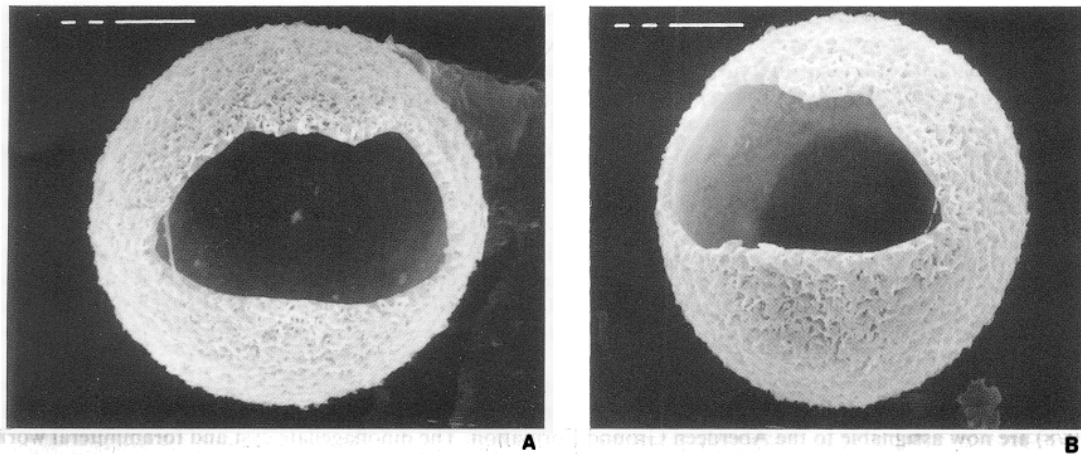
TEXT-FIG. 4. Stereoscan photomicrographs of *Bitectatodinium tepikiense* Wilson, × 1200. A, specimen MPK 5276, Norwegian Sea, dorsal view with archeopyle and camerate 3″ apical margin and planate 4″ margin. B, specimen MPK 5277, Norwegian Sea, oblique dorsal view with planate 4″ apical margin.

The presence of *O. israelianum* (Rossignol) Wall (Pl. 82, fig. 11) and *Tectatodinium pellitum* Wall (Pl. 82, fig. 10) in the younger assemblage probably does not suggest warmer-water conditions, as intimated in Stoker *et al.* (1985*b*), but may indicate reworking from Early Pleistocene sediments. Similarly Palaeogene reworking is prevalent throughout the Aberdeen Ground Formation.

The remaining part of the dinoflagellate spectrum can also be interpreted as indicative of north-temperate to arctic conditions but perhaps with some increasing uphole influence from the North Atlantic. The presence of *A. andalousiensis* and *B. tepikiense* supports the north-temperate environment and the low proportions of *Protoperidinium* spp. (round, brown cysts) (Pl. 82, fig. 9) preclude the possibility of much sea-ice. *Protoperidinium* dinoflagellates are heterotrophs, and therefore do not require the presence of light to survive (Bujak 1984; Dale 1985). This is reflected in their distribution patterns along the Norwegian coast (Dale 1983) but less so in the maps of Harland (1983). However, there is a noticeable rise in the proportions of *Protoperidinium* spp. between 180 and 190 m in the sequence, possibly indicating a cooling of the environment and the introduction of seasonal ice-cover.

In addition to the type borehole, dinoflagellate cyst analyses were completed upon other sequences of the Aberdeen Ground Formation proved in additional North Sea boreholes. For instance Borehole 81/27 (see text-fig. 5) yielded rich dinoflagellate floras dominated by *T. pellitum* with subsidiary *Spiniferites* spp. and relatively low proportions of *O. centrocarpum* and *O. israelianum*. This kind of dinoflagellate cyst assemblage
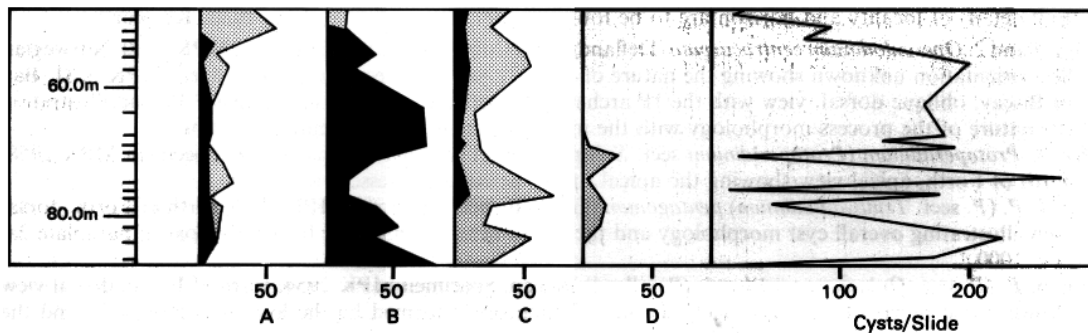


TEXT-FIG. 5. Dinoflagellate cyst biostratigraphy of the Aberdeen Ground Formation in Borehole 81/27, lat. 56° 32·71′ N., long. 0° 23·10′ W. Columns as in text-fig. 3.

is now regarded as indicating south-temperate to almost sub-tropical conditions in a neritic environment (Harland 1983; Cameron *et al.* 1984) and not cool temperate environments as incorrectly interpreted by Wall and Dale (1968*a*), following the pollen work of West (1961). The presence of both *O. israelianum* and *T. pellitum* are indicative of quite different environmental conditions from the succeeding cyst floras in which they are absent. Their presence is usually associated with Early Pleistocene sediments and the Matuyama palaeomagnetic reversal. Indeed Stoker *et al.* (1983) have recorded reversed palaeomagnetism from sediments of the Aberdeen Ground Formation in Borehole 81/27.

In summary, evidence indicates that the Aberdeen Ground Formation contains dinoflagellate cyst assemblages of wide-ranging environments including south-temperate to sub-tropical, north-temperate, and north-temperate to arctic. The dinoflagellate cysts taken with the palaeomagnetic results indicates an older Early Pleistocene part of the sequence and a younger ?Middle Pleistocene part, and indeed is part of the evidence used by Stoker *et al.* (1985*b*) to suggest a Tiglian to 'Cromerian Complex' age range. The Aberdeen Ground Formation is obviously a complex unit. It needs further study to circumscribe its age and environments of deposition more closely.

The climatic ameliorations described from benthonic Foraminifera and dinoflagellate cyst evidence for the sediments below the prominent seismic reflector in Borehole 75/33 (Harland *et al.* 1978; Gregory and Harland 1978) are now assignable to the Aberdeen Ground Formation. The dinoflagellate cyst and foraminiferal work would appear to suggest a Middle Pleistocene and not a Late Pleistocene age as originally suggested (Harland 1977; Harland *et al.* 1978; Gregory and Harland 1978). The radiocarbon dates quoted originally by Holmes (1977), which led to an underestimation of age, are thought to be invalid (Stoker *et al.* 1985*b*).

The recognition of a distinct change in the upper part of the Aberdeen Ground Formation between sediments containing such dinoflagellate cysts as *O. israelianum*, and *T. pellitum* as common components, and to a lesser extent by the presence of *Amiculosphaera umbracula* Harland (Pl. 81, figs. 5 and 6) and *Impagidinium multiplexum* (Wall and Dale) Lentin and Williams (not illustrated) together with various undescribed *Spiniferites* spp. and *Protoperidinium* spp., from sediments containing forms that commonly occur around the British Isles today has been used as a practical guide to delineate an Early/Middle Pleistocene boundary. It also marks the change between the fairly stable equable climate of the Early Pleistocene from the widely fluctuating situation of the Middle and Late Pleistocene. Studies by Wall and Dale (1968*a*), Reid and Downie (1973), and Harland (unpubl. data) suggest that the marked dinoflagellate change falls within the presently defined Middle Pleistocene possible as high as the Cromerian/Anglian boundary.

The early Pleistocene record is, nevertheless, characterized by sequences in which the proportions of various cysts fluctuate markedly (Wall and Dale 1968*a*; Cameron *et al.* 1984) and it is likely that these fluctuations together with some stratigraphical last and first appearances will lead to a dinoflagellate cyst biostratigraphy for the ?Early Pleistocene. The work of Harland (1984*a*, *b*) adds evidence from the oceanic record to these suggestions and points to the possibility that this boundary may correlate with the NN 19/20 boundary.

EXPLANATION OF PLATE 78

All the stereoscan photomicrographs are illustrated at a magnification of × *c*. 1200 unless otherwise noted. Full details of locality and horizon are to be found in the MPK registers of the BGS, Keyworth.

Figs. 1 and 2. *Operculodinium centrocarpum* (Deflandre and Cookson) Wall. 1, Specimen MPK 5280, Norwegian Sea, orientation unknown showing the nature of the cyst wall and processes. 2, specimen, MPK 5281, Bay of Biscay, oblique dorsal view with the 1P archeopyle formed by the loss of paraplate 3″ and illustrating the nature of the process morphology with the infundibular and multifurcate distal tips.

Fig. 3. *Protoperidinium* (*Protoperidinium* sect. *Selenopemphix*) *conicum* (Gran) Balech. Specimen MPK 2958, Firth of Forth, apical view showing the apical tuft of acicular processes, × *c*. 1000.

Fig. 4. *P.* (*P.* sect. *Trinovantedinium*) *pentagonum* (Gran) Balech. Specimen MPK 2956, Firth of Forth, dorsal view illustrating overall cyst morphology and the broad hexa I archeopyle formed by loss of paraplate 2a, × *c*. 1000.

Fig. 5. *P.* (*P.* sect. *Quinquecuspis*) *leonis* (Pavillard) Balech. Specimen MPK 2954, Firth of Forth, dorsal view showing cyst morphology particularly the hexa I archeopyle formed by the loss of paraplate 2a and the continuous paracingulum, × *c*. 1000.

Fig. 6. *Nematosphaeropsis labyrinthea* (Ostenfeld) Reid. Specimen MPK 5282, Bay of Biscay, orientation unknown, overall cyst morphology and ribbon trabeculae.

PLATE 78
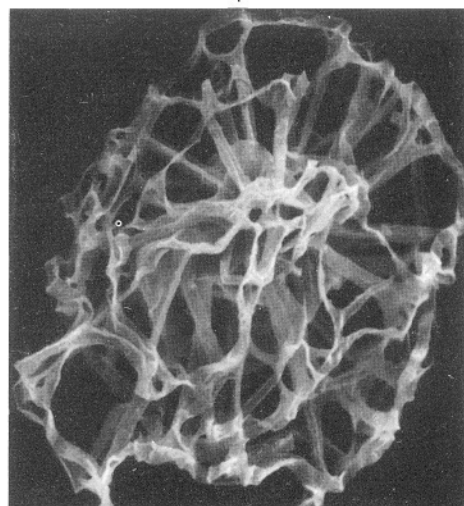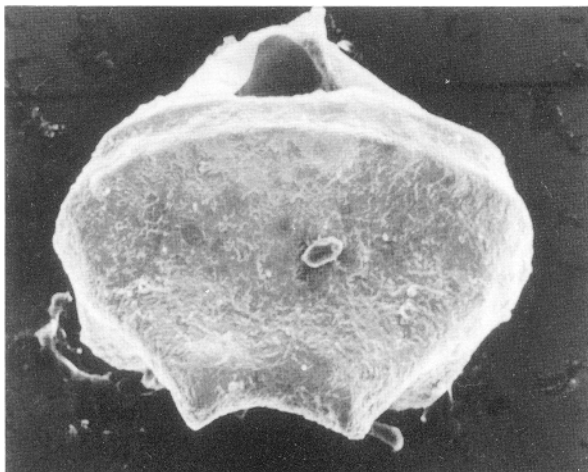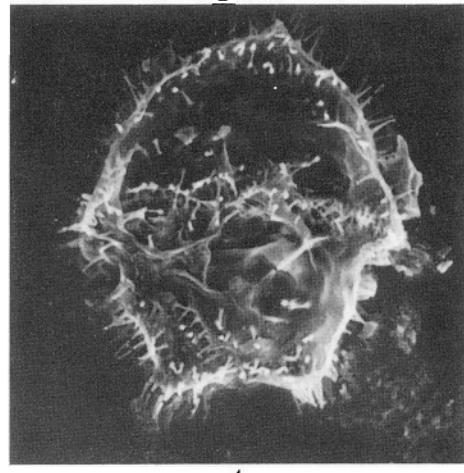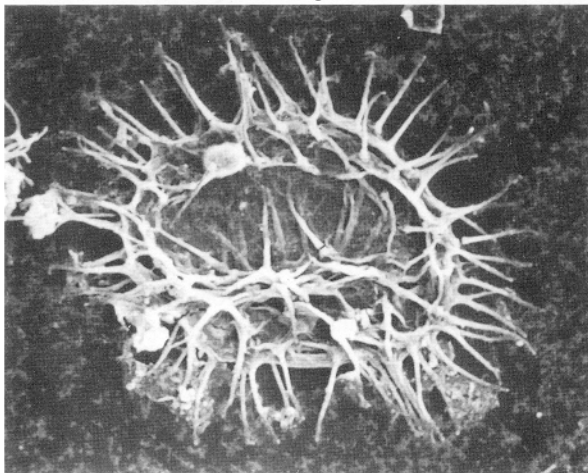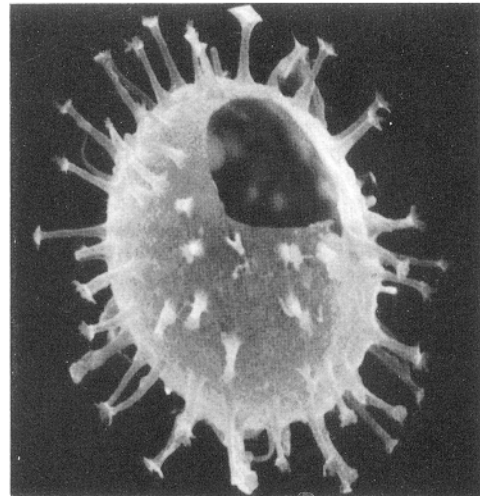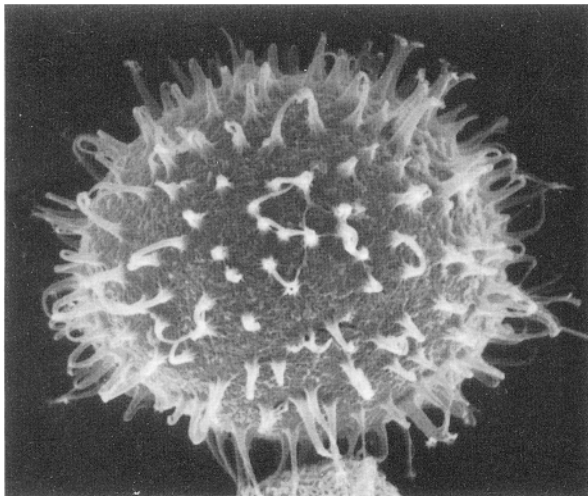


HARLAND, *Operculodinium, Protoperidinium, Nematosphaeropsis*
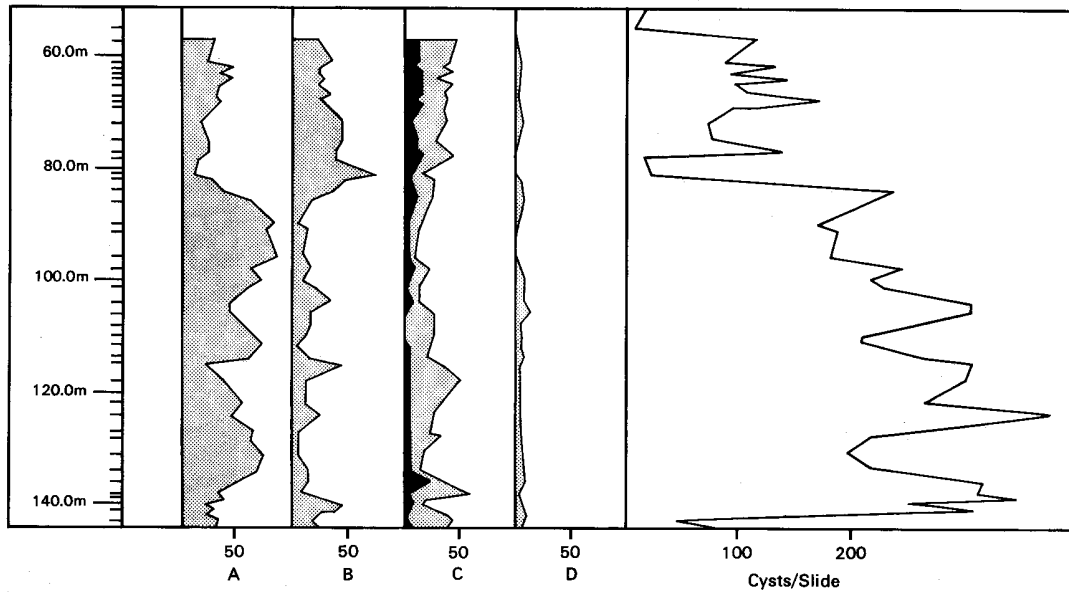
TEXT-FIG. 6. Dinoflagellate cyst biostratigraphy of the Ling Bank Formation in Borehole 81/34. Columns as in text-fig. 3.

*Ling Bank Formation*

The type sequence for the Ling Bank Formation is to be found in Borehole 81/34 from 55·0 m to 142·0 m. The formation consists of dense silts and silty sands with interbedded sands and clays especially in the upper part. The sediments are normally magnetized and probably part of the Brunhes Normal Epoch. Dating of this formation is difficult but Stoker *et al.* (1985*a* and *b*) have suggested a Holsteinian to Saalian (Hoxnian to early Wolstonian) age.

The dinoflagellate cyst spectrum for the type sequence (text-fig. 6) reveals a series of favourable assemblage that can be subdivided at about 83·0 m depth. The older is dominated by *O. centrocarpum* with *Spiniferites* spp. and lower proportions of *B. tepikiense* and *Protoperidinium* spp. This phase indicates a marked influence of the North Atlantic Current (Harland 1983), and without doubt can be attributed to an interglacial stage. Also present in this interval is *Achomosphaera andalousiensis*, particularly towards the base and top with a maximum proportion of 22·5 % at a level of 135·9 m (text-fig. 6), *N. labyrinthea* (Pl. 79, fig. 6) which like *A. andalousiensis* occurs towards the top and bottom, *P. conicum* (Pl. 78, fig. 3; Pl. 82, fig. 6) towards the middle and base, *P. pentagonum* (Pl. 78, fig. 4; Pl. 82, figs. 3 and 4) in the middle part of the sequence only and various *Spiniferites* spp. The *Spiniferites* spp. include *S. elongatus* Reid (Pl. 80, fig. 6) which occurs throughout, and

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EXPLANATION OF PLATE 79

All the stereoscan photomicrographs are illustrated at a magnification of × *c*. 1200 unless otherwise noted. Full details of locality and horizon are to be found in the MPK registers of the BGS, Keyworth.

Figs. 1 and 2. *Spiniferites ramosus* (Ehrenberg) Loeblich and Loeblich. 1, specimen MPK 5283, Bay of Biscay, dorsal view to show the 1P reduced archeople formed by the loss of paraplate 3″, the paratabulation and the trifurcate processes with bifid distal tipes. 2, specimen MPK 5284, Bay of Biscay, slightly oblique dorsal view.

Figs. 3–6. *S. lazus* Reid. 3, specimen MPK 5285, north-eastern Atlantic Ocean, oblique dorsal view to illustrate the 1P reduced archopyle formed by the loss of paraplate 3″ and the fenestrate nature of the process bases. 4, detail of fenestrate process base, × *c*. 12 000. 5, specimen MPK 5287, Bay of Biscay, dorsal view to show archeopyle, paratabulation, and deeply trifurcate nature of the processes. 6, detail of trifurcation of process together with the fenestrate process bases, × *c*. 2400.

PLATE 79
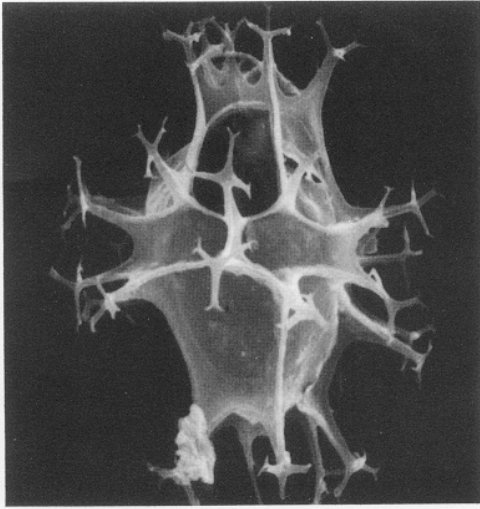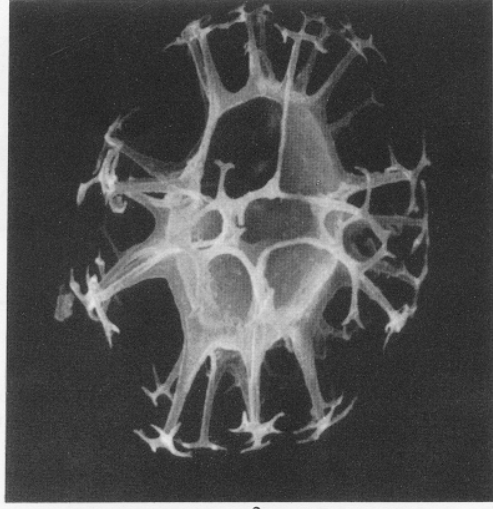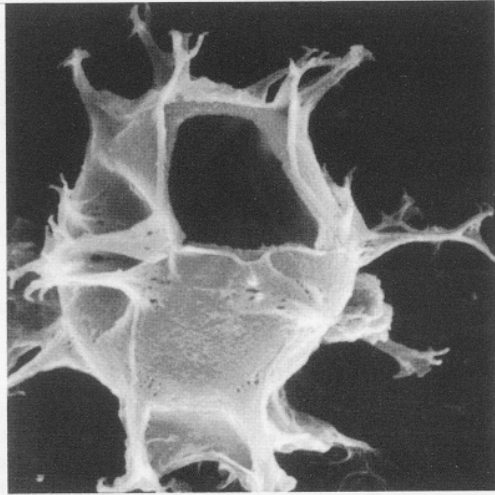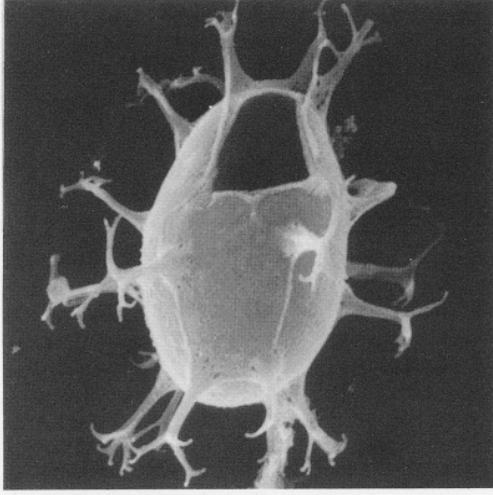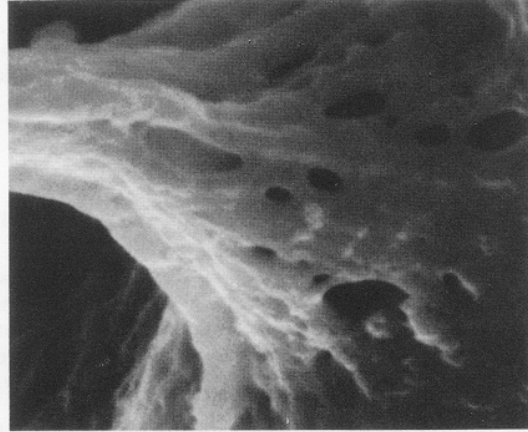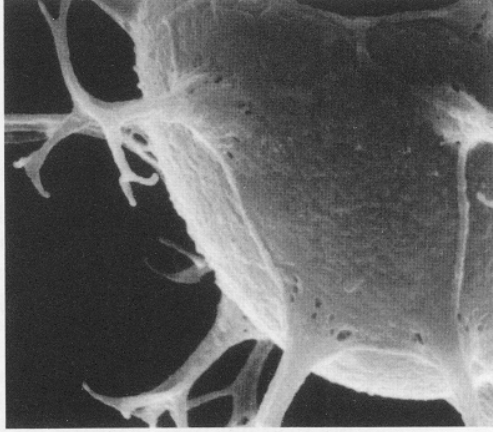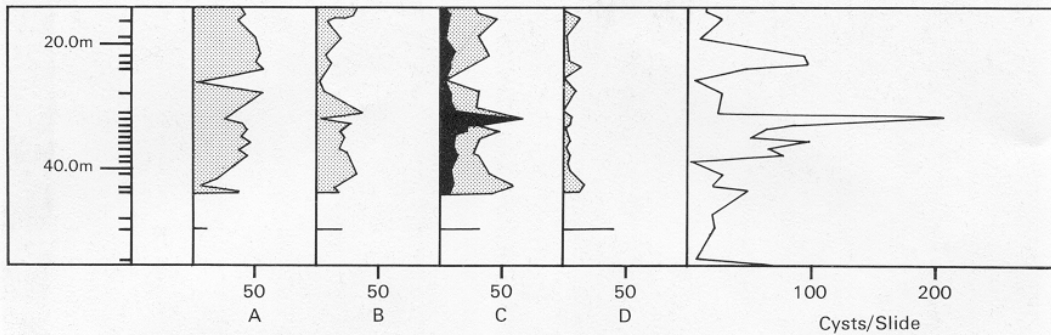
TEXT-FIG. 7. Dinoflagellate cyst biostratigraphy of the Fisher Formation in Borehole 81/34. Columns as in text-fig. 3.

*S. mirabilis* and *S. ramosus* (Pl. 79, figs. 1 and 2) that occur more frequently in the middle part of the sequence. This pattern can be interpreted as indicative of changing conditions within the interglacial with a cool initiation, a warm middle period, and a cool final phase.

   Above 82·0 m the character of the assemblages changes with samples showing a reduction in specimen numbers. There is a marked decrease in the proportion of *O. centrocarpum* with a reciprocal increase in the proportions of *B. tepikiense* and *Spiniferites* spp. especially *A. andalousiensis*. *S. elongatus* is consistently present, with *S. membranaceus* (Pl. 82, figs. 7 and 8) and *S. ramosus* occurring occasionally. This part of the sequence can be interpreted as the onset of poorer environmental conditions at the end of the interglacial possibly due to a more north-temperate to arctic influence. The penetration of the North Atlantic Current may not be as great but it is unlikely that the area was much affected by ice-cover because there is a lack of heterotrophic *Protoperidinium* species (Dale 1983, 1985).

   Dating of the Ling Bank Formation is difficult from the dinoflagellate cysts alone but undoubtedly it contains the record of an interglacial. Stoker *et al.* (1985*a* and *b*) favour a Holsteinian to Saalian age on general stratigraphic relationships.

*Fisher Formation*

The Fisher Formation type sequence occurs in Borehole 81/34 between 15·3 and 55·0 m depth. The formation consists of over-consolidated clays and silty sands with occasional shell fragments and pebbles. The sediments are normally magnetized and are likely to be part of the Brunhes Normal Epoch, although a single reversed horizon has been noted (Stoker *et al.* 1985*b*). A Saalian (Wolstonian) age has been suggested for the formation (Stoker *et al.* 1985*b*) although Holmes (1977) recorded a late Devensian radiocarbon age of 23 170 years B.P. from partially lignitized wood from a commercial borehole.

   The dinoflagellate cyst spectrum (text-fig. 7) is poor with many of the recovered assemblages being represented by 100 specimens or less. This lack of recovery is in itself an indication of poor, unfavourable

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EXPLANATION OF PLATE 80

All the stereoscan photomicrographs are illustrated at a magnification of × *c*. 850 unless otherwise noted. Full details of locality and horizon are to be found in the MPK registers of the BGS, Keyworth.

Figs. 1–5. *Spiniferites mirabilis* (Rossignol) Sarjeant. 1, specimen MPK 5289, Bay of Biscay, dorsal view showing the 1P reduced archeopyle formed by the loss of paraplate 3″ and the extensive antapical membrane. 2, specimen MPK 5291, Bay of Biscay, dorsal view showing a rather less extensive antapical membrane but many trifurcate parasutural processes with bifid distal tips. 4, specimen MPK 5292, Bay of Biscay, oblique dorsal view showing a cluster of processes surmounting the apex. 5, specimen MPK 5293, Bay of Biscay, right lateral view showing the many parasutural processes.

Fig. 6. *Spiniferites elongatus* Reid. Specimen MPK 3990, Barents Sea, dorsal view showing the 1P reduced archeopyle, the elongate morphology and development of parasutural membranes, × *c*. 1200.

PLATE 80
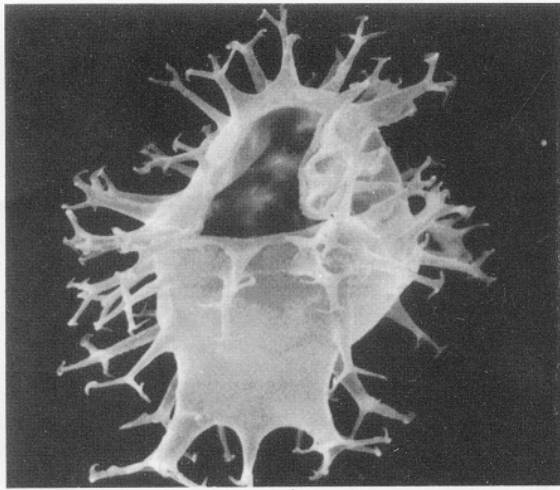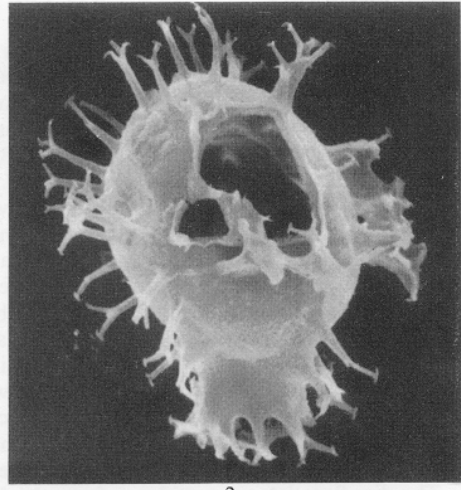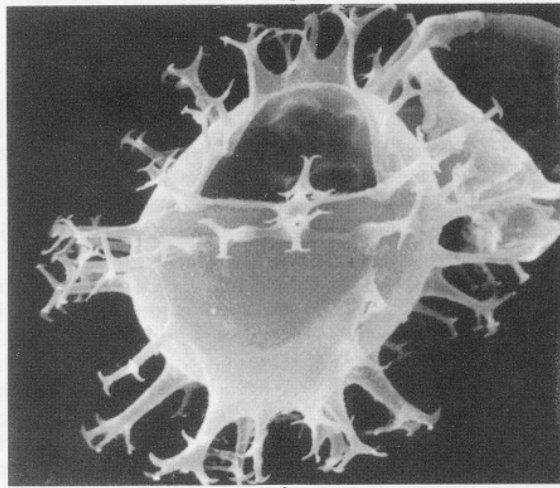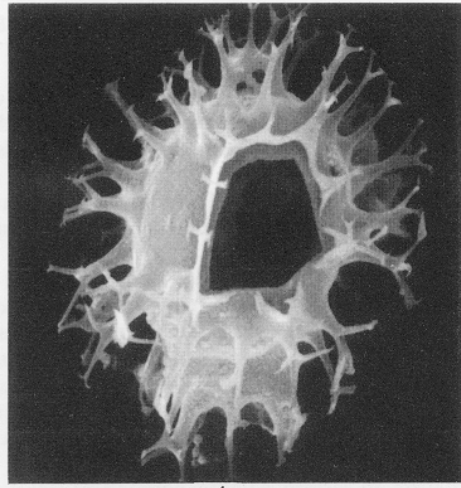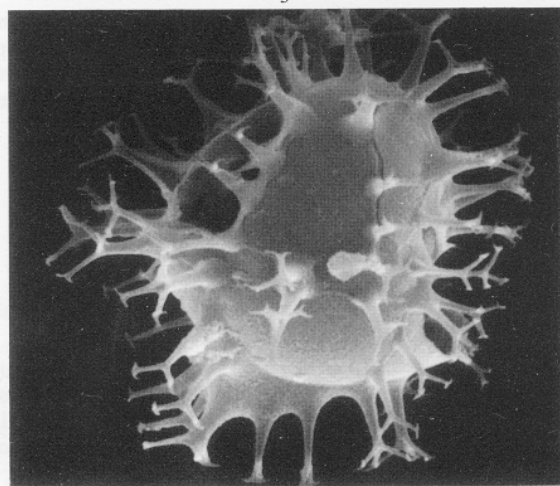


HARLAND, *Spiniferites*

conditions. The assemblages observed are for the most part dominated by *O. centrocarpum* and *Spiniferites* spp. *A. andalousiensis* is persistently present alongside *S. elongatus* which occurs as the ?ecophenotypic form of *S. frigidus* Harland and Reid (Harland and Sharp 1986). *Protoperidinium* cysts, as the round, brown morphotypes, occur throughout the formation albeit in small proportions. More importantly is the presence of *Multispinula minuta* Harland and Reid (Pl. 82, fig. 12), a form commonly associated with arctic environments in the Canadian offshore area (Harland *et al.* 1980; Mudie and Aksu 1984; Scott *et al.* 1984).

The dinoflagellate cyst spectrum is indicative of a somewhat intermediate situation between normal north-temperate conditions and severe arctic environments. The poor assemblages, the presence of *A. andalousiensis*, *B. tepikiense*, *M. minuta*, and *S. elongatus* all point to cold environments whereas the presence of richer assemblages may indicate rather open marine conditions with some influence from the North Atlantic. The presence of sea-ice, for instance, may have been seasonal but undoubtedly the environment is difficult to categorize. Variations in the cyst spectrum appear to suggest some short-lived climatic or environmental changes at 24·0 and 32·0 m with the latter yielding assemblages overwhelmingly dominated by *A. andalousiensis*. The factors causing such changes are unknown and indeed autecology data for *A. andalousiensis* is lacking (Harland 1983), although it may be more typical of cooler north-temperate to arctic waters (Long *et al.* 1986). The slight uphole increase in the proportions of *O. centrocarpum* and the decrease in *B. tepikiense* are probably in anticipation of more favourable environments.

The dinoflagellate cyst evidence from the Fisher Formation cannot in itself give a definitive age but the environmental interpretation suggests an assignment to a glacial and not an interglacial stage.

### Coal Pit Formation

The type section for the Coal Pit Formation occurs from 32·0 to 107·5 m in Borehole 81/37. The formation consists of dark-grey to brownish-grey, muddy pebbly sands and hard dark-grey, silty pebbly muds to silty muds, sandy silts, and fine to very fine sands. The sediments are mostly normally magnetized and can be assigned to the Brunhes Normal Epoch but some reversed polarity episodes have been identified possibly corresponding to the Blake Event and Laschamp Excursion (Stoker *et al.* 1985b). The Coal Pit Formation is thought to be of Saalian to Weichselian (Wolstonian to Devensian) age and includes the Eemian (Ipswichian) interglacial.

The dinoflagellate cyst spectrum for the Coal Pit Formation is divisible into three (text-fig. 8). This subdivision results from the recognition of a sequence of sediments between 72·0 to 102·0 m depth that contains particularly rich dinoflagellate cyst assemblages. These assemblages are all dominated by *O. centrocarpum* (up to 75 %) with minor proportions of *B. tepikiense*, *Spiniferites* spp., and *Protoperidinium* spp. Included within the *Spiniferites* column (text-fig. 8) is *A. andalousiensis* together with *S. elongatus;* occasionally present are the species *S. mirabilis* and *S. ramosus*. This assemblage is consistent with a more ameliorative environment of deposition than the remaining sediments of the Coal Pit Formation despite the presence of the more northerly cold water indicators *A. andalousiensis* and *S. elongatus*. The presence of *N. labyrinthea* and *S. mirabilis* also suggest an eastern Atlantic component (Harland 1983).

The remaining parts of the dinoflagellate cyst spectrum show a less productive aspect with lower proportions of *O. centrocarpum* and greater proportions of *B. tepikiense*, *Spiniferites* spp., and *Protoperidinium* spp. Although less favourable environmental conditions are envisaged, the lack of change in the dinoflagellate cyst proportions suggest some input from the North Atlantic. However, it is possible that some of these changes in productivity may result from lithological change.

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EXPLANATION OF PLATE 81

All the stereoscan photomicrographs are illustrated at a magnification of × *c.* 1200 unless otherwise noted. Full details of locality and horizon are to be found in the MPK registers of the BGS, Keyworth.

Figs. 1, 2, 4, 6. *Achomosphaera andalousiensis* Jan du Chêne. 1, specimen MPK 5294, Bay of Biscay, oblique dorsal view showing the 1P reduced archeopyle, the subdued parasutural ridges and the reticulate process tips. 2, specimen MPK 5295, Bay of Biscay, oblique dorsal view showing the reticulate process tips especially in the region of the paracingulum. 4, detail of process tips, × *c.* 2400. 6, specimen MPK 5296, Bay of Biscay, oblique dorsal view.

Figs. 3 and 5. *Amiculosphaera umbracula* Harland. 3, specimen, MPK 4339, Bay of Biscay, dorsal view showing the periphragmal archeopyle, × *c.* 1000. 5, specimen MPK 5298, Bay of Biscay, dorsal view, × *c.* 1000.
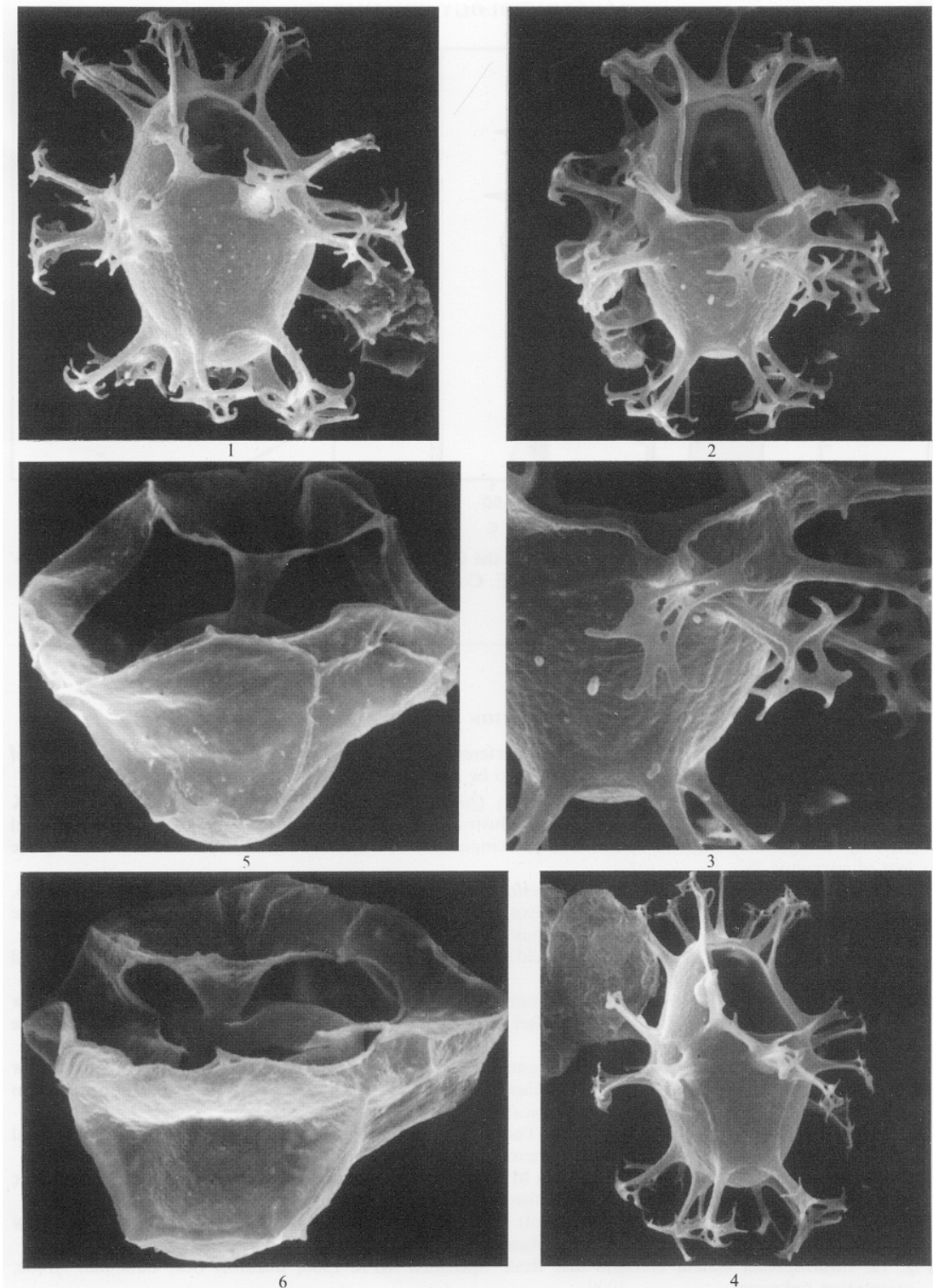
PLATE 81



HARLAND, *Achomosphaera, Amiculosphaera*
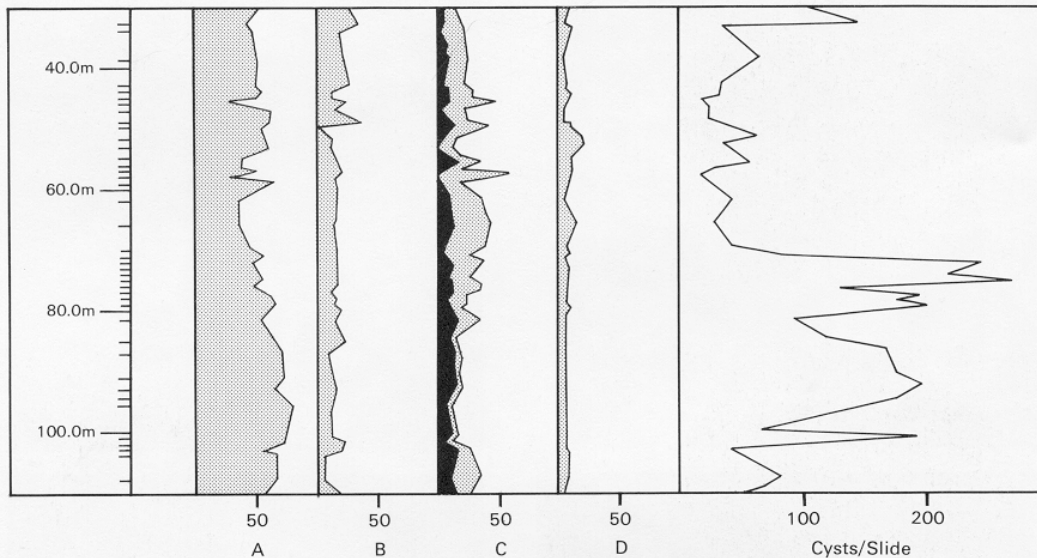
TEXT-FIG. 8. Dinoflagellate cyst biostratigraphy of the Coal Pit Formation in Borehole 81/37, lat. 56° 47·43′ N., long. 1° 31·47′ E. Columns as in text-fig. 3.

### EXPLANATION OF PLATE 82

All the photomicrographs are with Nomarski interference contrast and are illustrated at a magnification of ×500. Full details of locality and horizon are to be found in the MPK registers of the BGS, Keyworth.

Figs. 1 and 2. *Protoperidinium* (*Protoperidinium* sect. *Quinquecuspis*) *leonis* (Pavillard) Balech. Specimen MPK 2781, Firth of Forth. 1, ventral epicystal view illustrating the deeply inset parasulcus. 2, dorsal hypocystal view by transparency with the continuous paracingulum and single intercalary operculum formed by the loss of paraplate 2a.

Figs. 3 and 4. *P.* (*P.* sect. *Trinovantedinium*) *pentagonum* (Gran) Balech. Specimen MPK 1240, Irish Sea. 3, dorsal view by transparency with the broad hexa single intercalary archeopyle formed by the loss of paraplate 2a. 4, ventral view illustrating the continuous paracingulum and nature of the processes.

Fig. 5. *Nematosphaeropsis labyrinthea* (Ostenfeld) Reid. Specimen MPK 2963, Barents sea, ?oblique ventral view showing the overall morphology.

Fig. 6. *P.* (*P.* sect. *Selenopemphix*) *conicum* (Gran) Balech. Specimen MPK 2772, Firth of Forth, apical view of cyst showing the morphology and the offset standard hexa single intercalary archeopyle formed by the loss of paraplate 2a.

Figs. 7 and 8. *Spiniferites membranaceus* (Rossignol) Sarjeant. Specimen MPK 5299, North Sea. 7, dorsal view illustrating the single reduced precingular archeopyle formed by the loss of paraplate 3″. 8, optical section with the prominent and characteristic antapical membranous process.

Fig. 9. *P.* (*P.* sect. *Brigantedinium*) *conicoides* (Paulsen) Balech. Specimen MPK 1232, Firth of Clyde, dorsal view illustrating the single standard hexa intercalary archeopyle formed by the loss of paraplate 2a.

Fig. 10. *Tectatodinium pellitum* Wall. Specimen MPK 5595, BGS Ormesby Borehole, dorsal view showing the nature of the single precingular archeopyle formed by the loss of paraplate 3″.

Fig. 11. *Operculodinium israelianum* (Rossignol) Wall. specimen MPK 3117, Chillesford Clay, dorsal view illustrating the broad, single precingular archeopyle formed by the loss of paraplate 3″.

Fig. 12. ?*Multispinula minuta* Harland and Reid. Specimen MPK 1306, Beaufort Sea, Canadian Arctic, orientation unknown.

PLATE 82
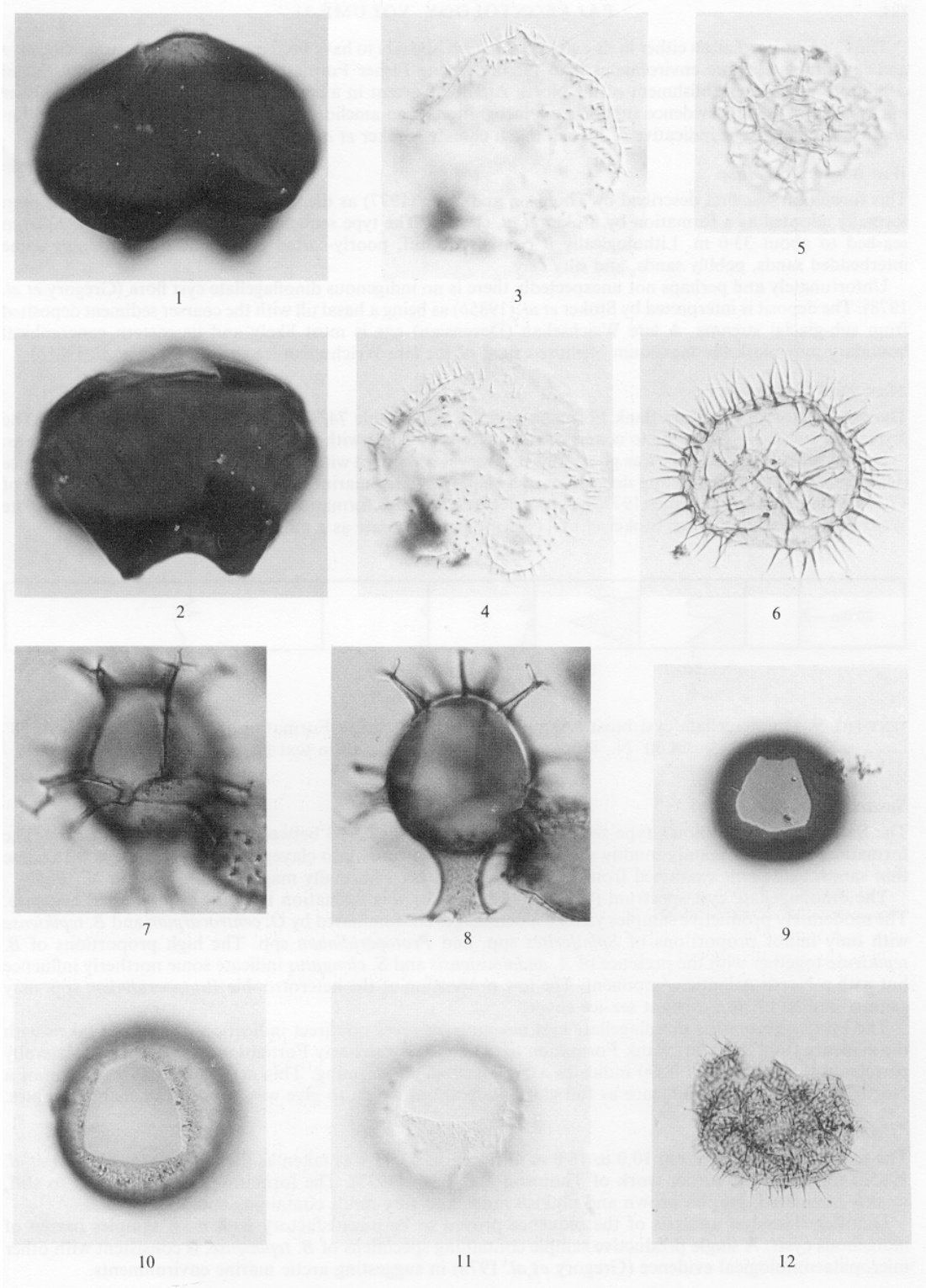


HARLAND, Quaternary dinoflagellate cysts

The Coal Pit Formation either in its entirety or in part appears to have been deposited in a more ameliorative and favourable climatic environment than the underlying Fisher Formation. This suggests full interglacial conditions and the establishment of the North Atlantic Current in a course not unlike that of today. Other micropalaeontological evidence supports the recognition of an ameliorative episode between 72·0 to 102·0 m depth but otherwise is indicative of a cold, harsh climate (Stoker et al. 1985b).

*Wee Bankie Formation*

This formation was first described by Thomson and Eden (1977) as the Wee Bankie Beds but has now been formally adopted as a formation by Stoker et al. (1985b). The type sequence occurs in Borehole 72/20 from sea-bed to about 33·0 m. Lithologically it consists of stiff, poorly-sorted polymictic till containing some interbedded sands, pebbly sands, and silty clay.

Unfortunately and perhaps not unexpectedly there is no indigenous dinoflagellate cyst flora (Gregory et al. 1978). The deposit is interpreted by Stoker et al. (1985b) as being a basal till with the coarser sediment deposited from sub-glacial streams. A late Weichselian (Devensian) age is most likely and its eastern geographical boundary may mark the maximum offshore extent of the late Weichselian ice sheet (Stoker et al. 1985b).

*Marr Bank Formation*

The type section of the Marr Bank Formation occurs in Borehole 74/77 between 2·0 and 21·0 m depth. The formation consists of very fine to coarse olive-grey to grey sands with occasional silty and gravelly horizons.

Dinoflagellate cyst recovery was poor. This recovery is consistent with other micropalaeontological evidence (Gregory et al. 1978) suggesting deposition in a shallow, glacio-marine environment. A radiocarbon date of 17 734±480 years B.P. (Holmes 1977) has been recorded for this formation. Although the date confirms a late Weichselian (Devensian) age Stoker et al. (1985b) regard the date as a minimum age.
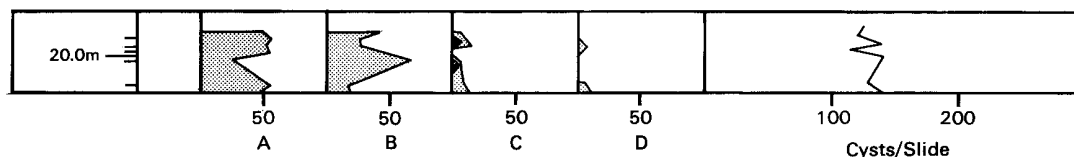


TEXT-FIG. 9. Dinoflagellate cyst biostratigraphy of the Swatchway Formation in Borehole 75/33, lat. 58° 4·30′ N., long. 0° 33·83′ E. Columns as in text-fig. 3

*Swatchway Formation*

The Swatchway Formation's type section occurs in Borehole 75/33 between 17·3 and 26·3 m depth. The formation comprises mainly muddy sands that pass northwards into clayey-silts and silty-clays with some thin sands. Sediments examined from this unit have all been normally magnetized (Stoker et al. 1985b).

The dinoflagellate cyst spectrum (text-fig. 9) drawn for this formation is based upon limited evidence. The moderately productive samples yielded assemblages co-dominated by O. centrocarpum and B. tepikiense with only minor proportions of Spiniferites spp. and Protoperidinium spp. The high proportions of B. tepikiense together with the presence of A. andalousiensis and S. elongatus indicate some northerly influence but with a North Atlantic component. The low proportion of the heterotrophic Protoperidinium spp. may suggest limited or non-existant sea-ice cover.

The evidence from the dinoflagellate cyst assemblages gives no direct indication of age, but taken with the evidence from the Marr Bank Formation to which the Swatchway Formation may be, in part, laterally correlated (Stoker et al. 1985b) indicates a period of slight warming. This may mark the beginning of a North Atlantic Current influence as full glacial conditions began to give way to more amenable climates.

*St Abbs Formation*

The sequence recovered from 10.0 to 16·0 m in Borehole 73/11 was taken as the type section (Stoker et al. 1985b) following the earlier work of Thomson and Eden (1977). The formation consists of soft to stiff, weakly laminated, grey to brown and pinkish muds and silty muds containing sporadic pebbles.

Dinoflagellate cyst analysis of the sequence proved to be unsatisfactory with most samples barren of indigenous cysts. A single productive sample containing specimens of B. tepikiense, is consistent with other micropalaeontological evidence (Gregory et al. 1978) in suggesting arctic marine environments.

It has been suggested that the St Abbs Formation is equivalent to the Errol Beds of the Forth and Tay estuaries (Thomson and Eden 1977) and, therefore, was deposited between 18 000 and 13 500 years B.P. (Peacock 1981). If this is correct then the St Abbs Formation is of late Devensian age.

## Witch Ground Formation

The Witch Ground Formation is divided into three members, which in ascending order are the Fladen, the Witch, and the Glenn. The type section of the formation occurs in Borehole 75/33 from sea-bed to 17·3 m depth. However, because the upper part of the sequence, the Glenn Member, is not well represented in Borehole 75/33, a vibrocore, 57/+00/9 at lat.: 57° 59.95′ N., long.: 0° 40·15′ E., was chosen as a supplementary type sequence and is here represented by sediments from the sea-bed to 1·3 m. The formation consists of soft, greenish-grey to greyish-brown clays and silts with the occasional sandy horizon. Sediments from the Witch Ground Formation recovered from Borehole 75/33 all have normal polarity and, therefore, are thought to be of a late Weichselian (Devensian) to Flandrian age (Stoker et al. 1985b).
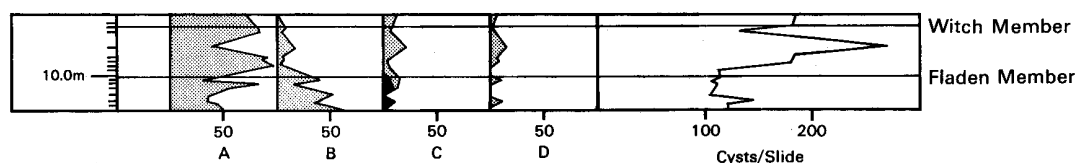


TEXT-FIG. 10. Dinoflagellate cyst biostratigraphy of the Witch Ground Formation in Borehole 75/33. Columns as in text fig. 3.

Dinoflagellate cyst analysis of the Witch Ground Formation from Borehole 75/33 (text-fig. 10) illustrates three significant factors. First there is an increased dinoflagellate productivity uphole, second a change from assemblages dominated by B. tepikiense to those dominated by O. centrocarpum, and thirdly the uphole disappearance of A. andalousiensis. The significance of these factors lies in the fact that all these changes occur at about the 10·0 m level in the borehole. This level may be interpreted as the change from a cold late Devensian environment to the warm Flandrian as modern oceanographic conditions became established, or alternatively, the onset of the Alleröd Interstadial.

This dinoflagellate cyst event coincides with the lithological boundary between the Fladen and Witch Members (Stoker et al. 1985b). Cyst evidence from the Fladen Member is consistent with deposition in a cold climate, but without the undue effects of sea-ice, giving way to an environment increasingly influenced by the North Atlantic.

The dinoflagellate cyst evidence suggests a late Devensian to early Flandrian age for the Fladen and Witch Members of the Witch Ground Formation but the boundary between them may not coincide with the Devensian/Flandrian boundary but with the onset of the Alleröd Interstadial. The Fladen Member can be correlated (Stoker et al. 1985b) to the Fladen Deposits of Jansen et al. (1979) who suggested a 15 000 to 18 000 years B.P. age.

The Witch Member contains a dinoflagellate cyst flora similar to modern assemblages (Reid 1975; Harland 1983) with influence of the North Atlantic Current. The assemblages contain high proportions of O. centrocarpum and lower proportions of B. tepikiense with S. mirabilis, P. pentagonum, and P. conicum. The occurrence of the last three species suggests conditions like those of today although the presence of A. andalousiensis, P. conicoides, and S. elongatus indicate some influence from the north. Jansen et al. (1979) suggested a 8700 to 15 000 years B.P. age for the Lower Witch Deposits, a correlative of the Witch Member (Stoker et al. 1985b). The recently discovered Vedde Ash equivalent in vibrocore 58/+00/111 by Long et al. (1986), which is dated at 10 600 years B.P. (Mangerud et al. 1984) would suggest a much older age for the top of the Witch Member.

The uppermost Glenn Member was not analysed for dinoflagellate cysts in its type sequence but it has been examined in vibrocore 58/+00/111 (Long et al. 1986). It is equivalent to Facies D of that sequence and includes the Vedde Ash. The dinoflagellate cyst record illustrates a lower colder period (Facies C) thought to be attributed to the Younger Dryas cooling between 10 000 and 11 000 years B.P., and an upper warm period (Facies D) with the establishment of the present day oceanography.

*Forth Formation*

The type section of the Forth Formation occurs from sea-bed to 29·0 m depth in Borehole 71/33. The formation is divided into four members; the Fitzroy, the Largo Bay, the Whitethorn, and the St Andrew's Bay. Lithologically the Forth Formation consists of muds overlain by pebbly muddy sands and soft silty muds, and is considered (Stoker *et al.* 1985*b*) to be laterally equivalent to the Witch Ground Formation and therefore to late Weichselian (Devensian) to Flandrian age. This age is supported by a radiocarbon date of 7109 ± 60 years B.P. (Holmes 1977). The various members of the Forth Formation are described more fully than those of the Witch Ground Formation since the Largo Bay and St Andrew's Bay Members occur to the west of the central North Sea and the Fitzroy and Whitethorn Members to the east, in the Devil's Hole area (Stoke *et al.* 1985B) (see text-fig. 2)

Borehole 74/1 provides the type section for the Largo Bay member which occurs between 5·0 m to 25·0 m. Dinoflagellate cyst recovery was poor but the cyst *B. tepikiense* was noted as the commonest species together with a few *Protoperidinium* cysts. This evidence is consistent with cold environments but perhaps with little or no sea-ice since so few *Protoperidinium* spp. were observed. Gregory *et al.* (1978) detail further micropalaeonto-logical data suggestive of less than present day temperatures but not as cold as those suggested for the St Abbs Formation. Judging the evidence of climate and the stratigraphical relationship of this member with its associated strata Stoker *et al.* (1985*b*) believe deposition occurred during the late Weichselian (Devensian) between 10 000 and 13 500 years B.P.

The type section for the Fitzroy Member occurs in Borehole 81/39 between 11·0 and 60·0 m depth. Palaeomagnetic analysis indicates normal polarity. The dinoflagellate cysts are generally sparse or absent in the sediments. Assemblages recovered are dominated by *O. centrocarpum* together with *B. tepikiense* and fewer *Spiniferites* spp. and *Protoperidinium* cysts. Evidence points to cool climatic conditions with some influence from the North Atlantic Current and little sea-ice. The Fitzroy Member is thought to be in part laterally equivalent to the Largo Bay Member and the Fladen Member of the Witch Ground Formation (text-fig. 2), and between 10 000 and 13 500 years B.P. in age (Stoker *et al.* 1985*b*).

The St Andrew's Bay Member has its type section in Borehole 71/33 between the sea-bed and 23·0 m. The dinoflagellate cyst recovery from the St Andrew's Bay Member was extremely poor. *Protoperidinium* cysts, *B. tepikiense* and *O. centrocarpum* were in evidence but no consistent picture emerged. Deposition in a cold, unfavourable environment is suggested possibly in relation to sea-ice, and considerable reworking was noted throughout. Further micropalaeontologial data, consistent with a cool environment, are given in Gregory *et al.* (1978). The dinoflagellate cyst and micropalaeontological evidence would, therefore, tend to disprove an early Flandrian (7000 to 10 000 years B.P.) age as suggested by Stoker *et al.* (1985*b*) and would appear to be more consistent with a late Devensian age.

The type section for the Whitethorn Member occurs in BGS Borehole 81/39 between the sea-bed and 11·0 m. Palaeomagnetic work (Stoker *et al.* 1985*b*) indicates normal polarity. Unfortunately only a single sample has been analysed for its dinoflagellate cysts and this yielded an assemblage dominated by *O. centrocarpum* (*c.* 85 %). This is comparable to modern assemblages from the area (Reid 1975; Harland 1983) and is indicative of similar oceanographic conditions. At present there is insufficient data to compare with the analyses of the Witch Ground Formation (Long *et al.* 1986) of similar age. Stoker *et al.* (1985*b*) indicate a Holocene age for this member.

*Summary*

Interpretation of the Quaternary dinoflagellate cyst record of the North Sea sequences allows a subdivision into favourable and unfavourable units. It is apparent that apart from the thick and extensive Aberdeen Ground Formation most of these units fall within defined seismostratigraphic formations (Stoker *et al.* 1985*b*). This reflects differences in the character of the units due to changes in the environment of deposition and hence the engineering properties of the material.

Although the sequence is fully discussed in Stoker *et al.* (1985*a*, *b*) it is worth stressing, that apart from the complex of environments in the Aberdeen Ground Formation, a number of ameliorative or interglacial episodes are noted. These interglacials occur in both the Ling Bank and Coal Pit Formations.

Dating of the interglacial units is difficult as no definitive radiometric data are available. However, the seismostratigraphic relationships, and the occurrence of the interpreted Blake and Laschamp Excursions in sediments attributed to the Coal Pit Formation, indicate an Ipswichian age for the Coal Pit Formation and therefore a Hoxnian age is inferred for the Ling Bank Formation. The

dinoflagellate cysts are not of any assistance in dating these units as similar ameliorative assemblages are recorded from both.

However, of interest is the assemblage recovered from the ameliorative episode seen in Borehole 78/9 at lat.: 61° 30·65′ N, long.: 0° 49·78′ E. (Skinner and Gregory 1983), which because of its association to the Blake palaeomagnetic event is attributed to the Ipswichian. The dinoflagellate cyst assemblages are rich and dominated by *O. centrocarpum* below and *B. tepikiense* above. Foraminiferal evidence suggests a strong amelioration and water depth exceeding 70 m. The dinoflagellate cyst assemblage is most like that recorded from the ?Hoxnian Ling Bank Formation in proving a transition from *O. centrocarpum* to *B. tepikiense* dominated floras.

## COMPARISONS

Various comparisons can be made according to the stratigraphic level under discussion. Unfortunately none are wholly satisfactory and allow only for a rather piecemeal approach.

### Early Pleistocene

The Early Pleistocene of the North Sea is represented by the Aberdeen Ground Formation and is recognized on the occurrence of reversed palaeomagnetic sediments and the presence of certain species of dinoflagellate cysts and Foraminifera seemingly restricted to the Early Pleistocene around the British Isles. Notable among the dinoflagellate cysts are *Amiculosphaera umbracula*, *O. israelianum*, and *T. pellitum* with *Impagidinium multiplexum* and various undescribed *Spiniferites* and *Protoperidinium* cysts.

Dinoflagellate cysts were first described from the Early Pleistocene of the British Isles by Wall and Dale (1968*a*) in their study of Ludhamian to Baventian strata from The Royal Society's Borehole at Ludham, Norfolk. Further work by Reid and Downie (1973) on the Bridlington Crag and mine on the Pastonian Chillesford Beds (unpubl.) have indicated a last appearance of these assemblages within the earliest part of the Middle Pleistocene. The cyst assemblages always indicate climatic environments considerably warmer than those of today.

Recently, dinoflagellate work described in Cameron *et al.* (1984) documents assemblages of cysts through a series of formations in the southern part of the North Sea. These assemblages substantiate the general character of the Pliocene/Early Pleistocene as noted above. Fluctuations in the proportions of some species appear to be controlled by changes in water mass characteristics, i.e. influence of more oceanic water and changes in sea-level, rather than by changes in climate.

It has proved difficult to correlate the palaeomagnetics and dinoflagellate cyst analyses. Some attempt was made in Cameron *et al.* (1984) but it is thought that the succession is badly affected by breaks in sedimentation. Further attempts are in progress on the Early Pleistocene succession from the Ormesby Borehole (text-fig. 1).

In the eastern Atlantic the Pliocene to Early Pleistocene dinoflagellate cyst record at Rockall (Harland 1984*b*) is poor whereas in the Goban Spur (Harland 1984*a*) the approximate Early to Middle Pleistocene boundary can be recognized, although a Plio/Pleistocene boundary cannot. The change in cyst assemblages across the Early/Middle Pleistocene boundary appears to coincide with the nannofossil NN 19/20 boundary.

The Early Pleistocene is characterized by particular groups of dinoflagellate cysts and although an abrupt change is noted between the Early Pleistocene and somewhere in the Middle Pleistocene no such change occurs between the Pliocene and Early Pleistocene. No doubt some of the reasons behind the latter are the result of few studies but nevertheless both Pliocene and Lower Pleistocene sediments contain similar cyst floras indicative of equable and stable climatic conditions. There is an obvious need to study more closely Pliocene and Early Pleistocene cyst floras not only to document the many new species that are undoubtedly present, but also to understand better the nature of the environmental changes.

*Middle–Late Pleistocene*

The Middle to Late Pleistocene record in the North Sea occurs within a number of seismostratigraphic units. It is characterized by normally magnetized sediments and severely fluctuating climatic conditions. The dinoflagellate cyst record reveals, for the most part, severe cold, arctic-like environments with evidence of three climatic ameliorations. Cyst floras are generally of low diversity, low cyst recruitment, and dominated by north-temperate to arctic forms. Ameliorations have been noted toward the top of the Aberdeen Ground Formation, the Ling Bank and Coal Pit Formations and can be recognized by the rise in cyst recruitment and the greater diversity of the cyst floras. Species that signify North Atlantic water or an oceanic influence together with north-temperate species become common.

Studies from the eastern Atlantic have recognized obvious interglacials both in the Rockall area (Harland 1984*b*) and the Goban Spur (Harland 1984*a*). However, first order correlations between the dinoflagellate cyst floras and oxygen isotope records have not been achieved but it is thought possible Ipswichian and Hoxnian sequences are present.

Unfortunately the Middle to Late Pleistocene of the southern part of the North Sea has not yielded good sequences of dinoflagellate cysts and indeed Cameron *et al.* (1987) indicate major hiatuses in southern North Sea sequences. Comparisons, therefore, cannot be made to the more complete northern North Sea successions.

*Latest Pleistocene–Holocene*

Dinoflagellate cyst studies reveal that the changes from full glacial conditions through to the modern oceanographic situation are clearly recorded even to the recognition of the Younger Dryas cooling (Long *et al.* 1986). The chronostratigraphy is assisted by the recognition of the Vedde Ash equivalent dated at 10 600 years B.P.

Particularly interesting is the clear signal, expressed by a change in the dinoflagellate cyst assemblages from those dominated by *B. tepikiense* to those dominated by *O. centrocarpum*, occurring at the Late Devensian–Alleröd/Bølling boundary. This signal may indicate the passage of the Polar Front across the north-eastern part of the Atlantic and the retreat of ice-dominated waters from the Atlantic Ocean and North Sea.
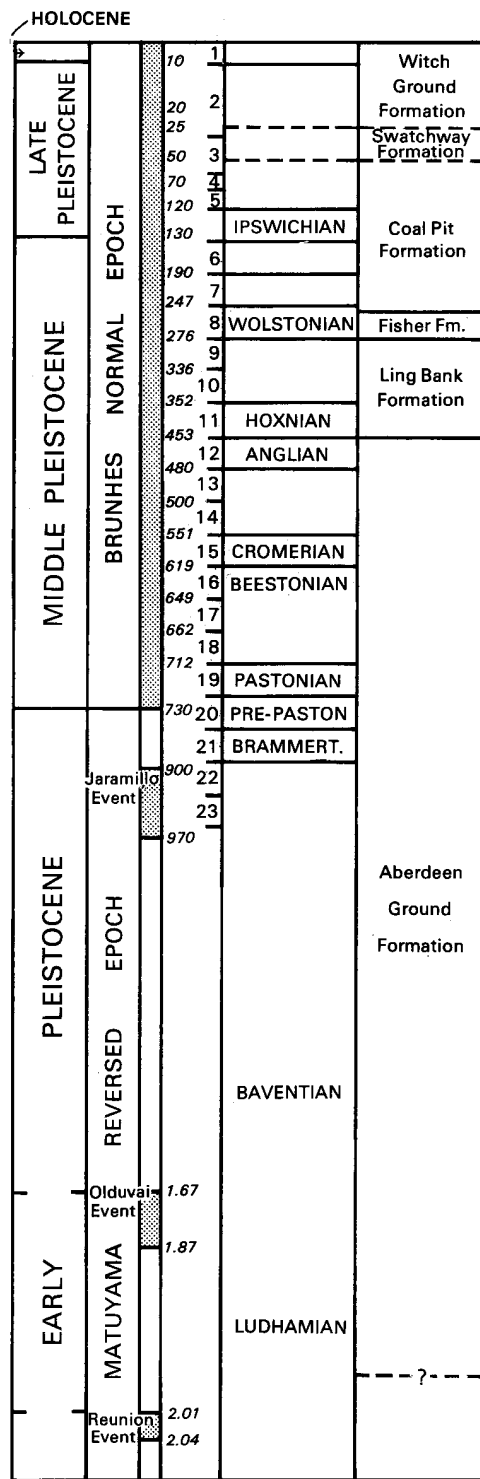
This singular event possibly dated from between 13 000 and 11 000 years B.P. is seen in the dinoflagellate cyst signal from the North Sea (Long *et al.* 1986, herein), the Goban Spur (Harland 1984*a*; DSDP Holes 548 and 549A), the Rockall Plateau (Harland 1984*b*; DSDP Hole 552A), Norwegian Sea (Harland 1984*c*; Vema Core 23-76) and has been recognized also by Turon (1981) from the Rockall Channel and by Harland (1987) and Stoker *et al.* (1987) in the Northern Rockall Trough and Faeroe–Shetland Channel.

Unfortunately there is insufficient evidence from these studies to comment on the exact timing of this event, which is known otherwise to be linked to the deglacial history of the North Atlantic (Duplessy *et al.* 1981; Ruddimann and McIntyre 1981) but it is worth stressing that the dinoflagellate cyst signal is clear, characteristic, and can be traced over a large area of the North Atlantic and North Sea. Work from the north-west continental shelf margin of the British Isles (Harland 1987; Stoker *et al.* 1987) and in the Minch (unpubl.) on similar sequences of thick late Devensian and Flandrian sediments indicate the possibility of further precision.

## CONCLUSIONS

An attempt has been made to synthesize the contribution dinoflagellate cyst research has made to the understanding of offshore Quaternary stratigraphy over the past decade or so. The use of dinoflagellate cyst biostratigraphy in offshore marine Quaternary sequences has assisted in the elucidation of events occurring within the Quaternary on the continental shelf. Dinoflagellate cyst studies are capable of recognizing glacial/interglacial cycles as well as interstadial events and have brought new information to the understanding of Early Pleistocene palaeoenvironments. High resolution stratigraphy is also possible within the latest Pleistocene and Holocene and events

TEXT-FIG. 11. The North Sea Quaternary succession in context of the established chronostratigraphy, palaeomagnetics, and oxygen isotope stratigraphy (based largely upon Jenkins *et al.* (1985)).



| | | | | | |
|---|---|---|---|---|---|
| | | | 10 | 1 | Witch Ground Formation |
| LATE PLEISTOCENE | | | 20 | 2 | |
| | | | 25 | | Swatchway Formation |
| | | | 50 | 3 | |
| | EPOCH | | 70 | 4 | |
| | | | 120 | 5 | |
| | | | 130 | | IPSWICHIAN | Coal Pit Formation |
| MIDDLE PLEISTOCENE | NORMAL | | 190 | 6 | |
| | | | 247 | 7 | |
| | | | 276 | 8 | WOLSTONIAN | Fisher Fm. |
| | | | 336 | 9 | Ling Bank Formation |
| | | | 352 | 10 | |
| | BRUNHES | | 453 | 11 | HOXNIAN |
| | | | 480 | 12 | ANGLIAN |
| | | | 500 | 13 | |
| | | | 551 | 14 | |
| | | | 619 | 15 | CROMERIAN |
| | | | 649 | 16 | BEESTONIAN |
| | | | 662 | 17 | |
| | | | 712 | 18 | |
| | | | | 19 | PASTONIAN |
| | | | 730 | 20 | PRE-PASTON |
| | | | | 21 | BRAMMERT. |
| | Jaramillo Event | | 900 | 22 | |
| | | | | 23 | |
| | | | 970 | | Aberdeen Ground Formation |
| PLEISTOCENE | EPOCH | | | | |
| | REVERSED | | | | BAVENTIAN |
| EARLY | Olduvai Event | | 1.67 | | |
| | MATUYAMA | | 1.87 | | |
| | | | | | LUDHAMIAN |
| | Reunion Event | | 2.01 | | |
| | | | 2.04 | | |

HOLOCENE

occurring over two or three thousand years can be recognized. Unlike other organisms, dinoflagellate cysts are unique in their correlation potential from deep-ocean sediments, continental slope, shelf, and nearshore marine sediments. Dinoflagellate cyst spectra will undoubtedly prove as useful offshore as pollen diagrams have proved onshore.

Finally there is potential in gaining palaeoceanographic information from dinoflagellate cyst analysis. Research points to the recognition of water masses, the documenting of surface and deep-water currents, and the recognition of the polar front and ice margins.

Text-fig. 11 attempts to place the North Sea sequence in terms of the currently recognized chronostratigraphy, and oxygen isotope stages. I look forward to even greater precision and to a better understanding of marine sequences from the use of dinoflagellate cyst analysis.

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REX HARLAND

Biostratigraphy Research Group
British Geological Survey
Keyworth
Nottingham NG12 5GG