DINOFLAGELLATE CYST BIOSTRATIGRAPHY AND PALAEOENVIRONMENTS OF THE UPPER JURASSIC (KIMMERIDGIAN TO BASAL PORTLANDIAN) OF THE HELMSDALE REGION, EAST SUTHERLAND, SCOTLAND

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ABSTRACT

Palynomorph assemblages from the Upper Jurassic, fault - controlled submarine slope deposits, of east Sutherland have yielded miospores and microplankton in varying abundances. The *Adnatosphaeridium caulleryi* group, *Cribroperidinium* spp. and *Cyclonephelium hystrix* are abundant throughout the section. Shorter-ranging taxa include *Cribroperidinium longicorne*, *Dichadogonyaulax*? *pannea*, *Egmontodinium expiratum*, *Gochteodinia mutabilis*, *Kleithriasphaeridium porosispinum*, *Oligosphaeridium pulcherrimum sensu* Ioannides *et al*. 1977 and *Senoniasphaera jurassica*. The base of the *Pavlovia rotunda* and the top of the *Virgatopavlovia fittoni* ammonite zones are recognized by the appearance of *Muderongia* sp.A Davey 1979 and the extinction of *Dingodinium tuberosum* and *Occisucysta balia* respectively. The youngest rocks exposed are assigned to the *Progalbanites albani* ammonite Zone of the Lower Portlandian. Increase in the ratio of microplankton to miospores in the Upper Kimmeridgian and Lower Portlandian is interpreted as indicating increasing distance from the terrestrial source due to fault-controlled widening of the submarine shelf.

INTRODUCTION

The discovery and development of hydrocarbon reservoirs in the North Sea Basin and adjacent areas during the past two decades has stimulated research on coeval strata onshore. In 1976, hydrocarbons in commercial quantities were discovered in the Moray Firth, 22 km east of Helmsdale, and were subsequently developed as the Beatrice Field (Figure 1). This discovery renewed the interest in the onshore Jurassic exposures of the Moray Firth, as the Beatrice Field is unusual in that the nearby surface geology can be directly related to the subsurface structure.

Exposed on the coast between Brora and Helmsdale are Kimmeridgian and basal Portlandian sediments (Figure 1), which form part of a thick Jurassic succession that represents the northwest margin of a fault-controlled sedimentary basin underlying the present Moray Firth. Lithologically the section consists of an interbedded sequence of sandstones, bituminous shales and boulder beds, deposited on the downthrow side of the Helmsdale Fault. Many of the oilfields in the northern North Sea, particularly in the South Viking Graben, occur in similar structural settings (MacDonald 1985).

Palynomorphs extracted from the bituminous shales consist mainly of miospores and dinoflagellate cysts (subsequently termed dinocysts). The latter have been selected for biostratigraphical analysis in this study because of their more restricted ranges in the Upper Jurassic compared to miospores. The ratio of dinocysts to miospores can be used in palaeoenvironmental analyses especially when integrated with sedimentological studies.

The literature on the Helmsdale region Kimmeridgian is extensive and for comprehensive reviews of previous work see Bailey & Weir (1932) and Pickering (1984). Recent studies include palaeobotanical work on the fossil flora from Kintradwell and Lothbeg Point (van der Burgh & van Konijnenburg-van Cittert 1984), clay mineralogy (Hurst 1985) and sedimentological and facies analysis (MacDonald 1985).

APPROX POSITION OF FIG 1 →

GEOLOGICAL BACKGROUND

The geology of the Sutherland coast consists of a basement of metamorphosed Moinian sediments intruded by the Helmsdale Granite and unconformably overlain by Devonian Lower and Middle Old Red Sandstone deposits of the Orcadian Basin (Figure 1). The Helmsdale Fault separates these pre-Mesozoic rocks from a narrow coastal strip of Triassic and Jurassic strata, representing the northwest margin of a large Mesozoic sedimentary basin in which a total of 2300m of Jurassic sediments are present at the depocentre, 25 km east of Helmsdale (Chesher & Lawson 1983). This is one of the thickest Jurassic sections in the North Sea Basin (Brooks & Chesher 1975).

The Helmsdale Fault, active during Late Jurassic sedimentation, is one of a number of similar faults resulting from extensive rifting during the Late Jurassic and Early Cretaceous in this area. This rifting gave rise to the tilted horst blocks in the North Sea, evidence for which can be seen in angular unconformities in seismic sections (Selley 1976).

During the Mesozoic, the structure of the Moray Firth Basin seems to have broadly coincided with the Orcadian Basin that existed during Old Red Sandstone times (Chesher & Lawson 1983). Carboniferous sediments are not found either on- or offshore, although past deposition and subsequent erosion is inferred from the presence of Carboniferous spores within the Jurassic succession (Lam & Porter 1977; Windle 1979; Riley 1980) and clay mineral provenance (Hurst 1985). Basic volcanics of Carboniferous age are, however, found in well 12/23-1, northeast of the Beatrice Field (Linsley et al. 1980).

The Triassic continental clastics exposed around Golspie (9 km to the southwest of Brora) are derived from Devonian and Caledonide sources, rejuvenated by Hercynian movements (Linsley et al. 1980). This continental deposition is succeeded from the Hettangian to the Pliensbachian by fluvial to lagoonal and latterly shallow marine siltstones, sandstones and shales (Batten et al. 1986). Overlying this is a broadly transgressive sequence of sandstones, carbonaceous shales and coal of Bathonian age. The succeeding Callovian to Middle Oxfordian strata, exposed around Brora, represent stable, shallow-water marine shelf sedimentation. Increased activity of the Helmsdale Fault from the late Oxfordian to the Portlandian led to deepening of the basin, resulting in the deposition of the thick, fault-controlled Kimmeridgian to basal Portlandian succession of boulder beds, shales and sandstones.

APPROX. POSITION OF FIG. 2 →

STRATIGRAPHY

The Upper Jurassic section is exposed on the foreshore between Kintradwell and Dùn Glas, forming a narrow strip of coastline about 19 km long and up to one km wide (Figures 1 & 2), with a total estimated thickness of about 630m (MacDonald 1985). The strata reveal a complex array of boulder beds interdigitated with bituminous shales and sandstones which generally become younger to the northeast. Minor faults of up to several metres displacement are common and the whole succession has been deformed by simple, open, gently plunging folds (Pickering 1984).

In this study the lithostratigraphical nomenclature of Pickering (1984) is adopted, consisting of the Kintradwell Boulder Beds, the Allt na Cuile Sandstones and the Helmsdale Boulder Beds. The section has been dated using ammonites (Bailey & Weir 1932; Linsley 1972; Brookfield 1976), and with additional palynological data from Riley (1980) and the present study, a Rasenia cymodoce to Progalbanites albani ammonite Zone age is proposed (Figure 3). Age relations from structural studies by MacDonald (1985) generally confirm the biostratigraphy of earlier workers.

Exposed on the foreshore at Kintradwell are the Kintradwell Boulder beds (Figure 1), which consist of black shales with lesser amounts of sandstones and several boulder beds. Bedding is irregular with common evidence of syn-sedimentary deformation, such as slides, faulting and folding. They are assigned to the cymodoce ammonite Zone (Linsley 1972) and the maximum thickness is estimated to be 85m (Pickering 1984).

A sequence of bioturbated mudstones and sandstones exposed on the foreshore between the Loth River and the Allt na Cuile (Figure 2) are interpreted by Macdonald (1985) to be of cymodoce or Pictonia baylei ammonite Zone age as they underlie the Allt na Cuile Sandstones. Deposition in a well oxygenated shelf environment, similar to that of the Callovian and Oxfordian strata of the Brora region is suggested by the bioturbation and general lack of sapropelic kerogen residues in palynological preparations (MacDonald 1985). These conditions probably represent the last of the Jurassic shallow water or marginal marine sedimentation, prior to major basin margin faulting and subsidence (MacDonald 1985).

Outcrops of the Allt na Cuile Sandstones are present at Lothbeg Bridge, Lothbeg Point and in the gorges of the Allt Choll and Allt na Cuile (Figure 2). The succession consists of massive sandstones, cross-bedded sandstones, laminated carbonaceous sandstones and black shales with limestone nodules, with an estimated total thickness of 120m (Pickering 1984; MacDonald 1985). As defined by Pickering (1984), the Allt na Cuile Sandstones include the Loth River Shales of Brookfield (1976) and Lam & Porter (1977) and range in age from at least the basal cymodoce to the basal Aulacostephanoides mutabilis ammonite Zone. The contact between the Allt na Cuile Sandstones and the Kintradwell Boulder Beds is not exposed and Neves & Selley (1975) have the sandstones underlying the boulder beds, whereas Lam & Porter (1977) and Pickering (1984) place the sandstones above the boulder beds. From field relations and palaeontological evidence, MacDonald (1985) regards the two sequences as approximate lateral equivalents.

The laminated carbonaceous sandstones at Lothbeg Bridge are very similar to the "tiger-stripe" facies described from Upper Jurassic sands in the Viking Graben of the northern North Sea Basin by Stow et al.(1982). In the Brae oilfield, these sands are interpreted as a series of coalescing submarine fans, with associated fault scarp boulder beds. Pickering (1984) interpreted the Allt na Cuile Sandstones as submarine channel deposits whereas MacDonald (pers. comm.) believes they are sub-wave base, but relatively shallow-water deposits.

The Helmsdale Boulder Beds, exposed on the foreshore between Lothbeg Point and Dùn Glas (Figure 1), are estimated to be 500m thick (MacDonald 1985) though considerable lateral facies variation makes this difficult to calculate accurately. In age they range from the *mutabilis* to the *albani* ammonite Zone (Linsley 1972; Riley 1980; this work). Linsley (1972) and Lam & Porter (1977) had suggested the *Pectinatites scitulus* ammonite Zone to be faulted out at Gartymore and the *Pectinatites hudlestoni* ammonite Zone to be present in the Helmsdale area but not exposed. From structural and sedimentological data, MacDonald (pers. comm.) assumed the section to be almost continuous, with only part of the *Pectinatites wheatleyensis* ammonite Zone unexposed at Helmsdale (Figure 2) and no evidence of faulting at Gartymore, although angular disconformities are present on the Helmsdale to Navidale and Gartymore foreshores.

APPROX. POSITION OF FIG. 3

Dominant lithologies are boulder beds, carbonaceous shales and sandstones in varying proportions throughout the section. At Portgower and Gartymore, boulder beds from one to nearly ten metres in thickness can be seen interdigitated with dark grey, laminated, sandy shales and numerous bedded sandstones. Contained within the boulder beds are randomly oriented blocks of Old Red Sandstone which range in size from several centimetres to the Portgower "fallen stack" (Bailey & Weir 1932) which measures 45 x 27 x 9m.

Between Helmsdale and Dùn Glas, the boulder beds become more numerous with reduced amounts of sandstone and shale. On the Dùn Glas foreshore, the Jurassic rocks form a breccia with the Helmsdale Granite as a result of shearing associated with the Helmsdale Fault (Pickering 1984).

Clast composition within the boulder beds is seen to change from Kintradwell to Dùn Glas. In the *cymodoce* and *mutabilis* ammonite zones the clasts are all composed of Jurassic sandstone, while from the Aulacostephanus eudoxus to the Aulacostephanus autissiodorensis ammonite zones they are both Jurassic and Old Red Sandstone, and in the Pectinatites elegans to the albani ammonite Zone only Old Red Sandstone clasts are present (MacDonald 1985).

SAMPLES AND PROCESSING TECHNIQUES

The thirty eight samples collected from shales and carbonaceous sandstones along the foreshore between Kintradwell and Dùn Glas were and subjected to standard palynological processing techniques (Batten & Morrison 1983). The stratigraphical positions and eight-figure national grid references of the sample locations are shown in Figure 3. Palynological preparations and figured specimens are deposited in the Marischal College Palynology Collection (MCP) of the Department of Geology and Mineralogy at the University of Aberdeen.

PALYNOMORPH PRESERVATION

Palynomorph preservation in these samples is variable. Miospores are generally moderately well preserved, probably due to their more robust nature compared to the dominantly thinner-walled dinocysts, most of which show evidence of physical degradation. Skolochorate cysts especially are rarely well preserved, most specimens having broken and tangled processes, often obscured by adhering amorphous organic matter. Other forms often show surface corrosion and occasionally contain framboidal pyrite. Dinocyst preservation tends to be poorest in the Lower Kimmeridgian and improves markedly in the younger strata examined, especially in the Pavlovia rotunda to albani ammonite zones. Only samples 52, 104 and 106 were found to be barren of palynomorphs. Sample 52 is a fine sandstone, while 104 and 106 were collected from an indurated shale in a shear zone associated with the Helmsdale Fault, these preparations consisting mainly of amorphous organic matter. Lam & Porter (1977) and Riley (1980) have also commented on the poor preservation of the dinocysts from the Helmsdale Boulder Beds. Dinocyst assemblages from the Kimmeridgian of Europe are often poorly preserved (Riding 1984).

SYSTEMATIC PALYNOLOGY

All the dinocysts species or groups encountered during the study are alphabetically listed below, together with author citations, full reference to which can be found in Lentin & Williams (1985). Species or groups which merit comment or discussion are marked with an asterisk (*). The plate and figure numbers are given where the species is illustrated.

Dinocyst Taxa

*Adnatosphaeridium caulleryi (Deflandre 1938) Williams & Downie 1969 group

Apteodinium nuciforme (Deflandre 1938) Stover & Evitt 1978

Cassiculosphaeridia magna Davey 1974

Chlamydophorella sp.

Chytroeisphaeridia chytroeides (Sarjeant 1962) Downie &

Sarjeant 1965 emend. Davey 1979

Cleistosphaeridium ehrenbergii (Deflandre 1947) Davey et al. 1969

C. polyacanthum Gitmez 1970

C. tribuliferum (Sarjeant 1962) Davey et al. 1969

Cribroperidinium globatum (Gitmez & Sarjeant 1972) Helenes 1984

C. granuligerum (Klement 1960) Stover & Evitt 1978

C. longicorne (Downie 1957) Lentin & Williams 1985, Pl.1, fig.1

*Cribroperidinium sp.A Davey 1982a, Pl.1, figs.2,3

*Cribroperidinium spp., Pl.1, figs.4,5

Cyclonephelium hystrix (Eisenack 1958) Davey 1978, Pl.1, fig.7

Dichadogonyaulax? pannea (Norris 1965) Sarjeant 1969, Pl.1, fig.6

Dingodinium tuberosum (Gitmez 1970) Riley in Fisher & Riley 1980, Pl.1, fig.8

Egmontodinium expiratum Davey 1982a, Pl.1, fig.9

E. polyplacophorum Gitmez & Sarjeant 1972, Pl.1, fig.10

Ellipsoidictyum cinctum Klement 1960

Escharisphaeridia pocockii (Sarjeant 1968) Erkmen & Sarjeant 1980

Glossodinium dimorphum Ioannides et al. 1977, Pl.2, fig.1

Gochteodinia mutabilis (Riley in Fisher & Riley 1980) Davey 1982a, Pl.2, fig.3

Gonyaulacysta eisenackii (Deflandre 1938) Dodekova 1967 emend. Sarjeant 1982

G. jurassica (Deflandre 1938) Norris & Sarjeant 1965 emend. Sarjeant 1982

Hystrichodinium pulchrum Deflandre 1935

Hystrichosphaeridium petilum Gitmez 1970

Kleithriasphaeridium porosispinum Davey 1982a

Leptodinium antigonium Ioannides et al. 1977, Pl.2, fig.4

L. eumorphum (Cookson & Eisenack 1960) Sarjeant 1969

Meiourogonyaulax pila Gitmez & Sarjeant 1972

Mendicodinium groenlandicum (Pocock & Sarjeant 1972) Davey 1979

Muderongia simplex Alberti 1961, Pl.2, figs.8,9

*Muderongia sp.A Davey 1979, Pl.2, fig.5

Occisucysta balia Gitmez 1970, Pl.2, fig.7

*Oligosphaeridium pulcherrimum (Deflandre & Cookson 1955) Davey & Williams 1966 sensu Ioannides et al. 1977, Pl.2, fig.2

Pareodinia ceratophora Deflandre 1947 emend. Gocht 1970

Perisseiasphaeridium sp., Pl.2, fig.10

Prolixosphaeridium capitatum (Cookson & Eisenack 1960) Singh 1971

P. granulosum (Deflandre 1937) Davey et al. 1966

P. parvispinum (Deflandre 1937) Davey et al. 1969

Rhynchodiniopsis cladophora (Deflandre 1938) Below 1981

R. nealei (Sarjeant 1962) Jan du Chêne et al. 1985

Senoniasphaera jurassica (Gitmez & Sarjeant 1972) Lentin & Williams 1976, Pl.2, fig.6

Sentusidinium echinatum (Gitmez & Sarjeant 1972) Sarjeant & Stover 1978

S. pilosum (Ehrenberg 1854) Sarjeant & Stover 1978 emend. Erkmen & Sarjeant 1980

S. sparsibarbatum Erkmen & Sarjeant 1980

Sirmiodinium grossii Alberti 1961 emend. Warren 1973

Subtilisphaera? inaffecta (Drugg 1978) Bujak & Davies 1983

Systematophora areolata Klement 1960

S. penicillata (Ehrenberg 1843) Sarjeant 1980

Tubotuberella apatela (Cookson & Eisenack 1960) Ioannides et al. 1977 emend. Sarjeant 1982

Genus **Adnatosphaeridium** Williams & Downie 1966

Adnatosphaeridium caulleryi (Deflandre 1938) Williams & Downie 1969 group

Remarks: Included in this group are forms attributed to Adnatosphaeridium caulleryi (Deflandre 1938) Williams and Downie 1969, Hystrichosphaerina orbifera (Klement 1960) Stover and Evitt 1978 and Systematophora sp.1 Davey 1982a. The close similarity and process complexity of these species precludes separation in the present study, especially as all the specimens found are damaged and poorly preserved. Davey (1982a) stated that Systematophora sp.1 may fall within the range of variation acceptable for A. caulleryi. Hystrichosphaerina orbifera is similar to Systematophora sp.1 but has more complexly branched processes.

Dimensions: Central body diameter 54(57)64 µm.
Process length 20(23)28 µm.
6 specimens measured.

Occurrence: cymodoce to albani ammonite zones.

Genus **Cribroperidinium** Neale & Sarjeant 1962 emend. Helenes 1984

Cribroperidinium sp.A Davey 1982a

Plate 1, figs. 2,3

Remarks: Davey (1982a) noted that Cribroperidinium sp.A is morphologically similar to C. longicorne (Downie 1957) Lentin & Williams 1985 except that C. longicorne is more spherical, thinner walled and has poorer indications of paratabulation. The specimens of Cribroperidinium sp.A observed conform to Davey's description, though the wall is often not as densely intraperforate and the spines at the base of the apical horn are not usually as well developed on the specimens observed here.

Dimensions: Length 97(119)136 µm. Breadth 53(59)81 µm.
Horn length 20(40)49 µm. 5 specimens measured.

Occurrence: scitulus to albani ammonite zones.

Cribroperidinium spp.

Plate 1, figs.4,5

Remarks: This category includes forms in which there is a continuous gradation in morphological features thus making speciation difficult. The poor preservation and damaged nature of many of the specimens added to the problems involved. Helenes (1984) regarded the genus Acanthaulax Sarjeant 1968 as a possible junior synonym of Cribroperidinium and forms similar to Acanthaulax sp.A Ioannides et al. 1977 have been included in Cribroperidinium spp.

Occurrence: cymodoce to albani ammonite zones. Particularly abundant from the scitulus ammonite Zone upwards.

Genus **Muderongia** Cookson & Eisenack 1958

Muderongia sp.A Davey 1979

Plate 2, fig.5

Remarks: The specimens encountered in this study have large, well developed apical, lateral and antapical horns with the operculum normally remaining in place. They are similar to those illustrated by Davey (1979) in having an angular endocyst which normally extends into the proximal parts of the antapical horns. According to Davey (1979), Muderongia simplex Alberti 1961 has a characteristic subspherical rather than an angular endocyst. This differs from the original description which states (translated from the German) "The inner body lies close to the outer margin of the cyst, often it stetches out somewhat into the horns" (Alberti 1961, p.12). Thus it would seem that Muderongia sp.A conforms to the original diagnosis of Muderongia simplex, though there appear to be two separate species involved.

Dimensions: Overall length with apex 145(165)177 µm.
Overall breadth 93(111)128 µm.
10 specimens measured.

Occurrence: rotunda to albani ammonite zones.

Genus **Oligosphaeridium** Davey & Williams 1966 emend. Davey 1982a

Oligosphaeridium pulcherrimum (Deflandre & Cookson 1955) Davey & Williams 1966 sensu Ioannides et al. 1977

Plate 2, fig.2

Remarks: Riley (1979) considered the specimens illustrated by Ioannides et al. (1977) and Gitmez (1970) to have been wrongly assigned to O. pulcherrimum and considered them to probably represent a new species. The specimens found in this study are all poorly preserved with much adhering amorphous organic matter and many of their processes are broken or damaged. However, enough detail was seen to enable the specimens to be referred to O. pulcherrimum sensu Ioannides et al. 1977.

Dimensions: Central body diameter 46(49)55 µm.
Process length 29(33)41 µm.
7 specimens measured.

Occurrence: eudoxus to Pectinatites pectinatus ammonite zones.

BIOSTRATIGRAPHY

By the end of the Jurassic several invertebrate groups, particularly the ammonites, had become separated geographically into a southern Tethyan Realm and a Boreal Realm lying to the north (Arkell 1956; Casey 1971; Hallam 1971). The situation is further complicated by the presence of local provinces within these two realms, especially in the Boreal Realm where shallow continental seas had prevailed (Casey 1973). The difficulty of correlation between the provinces has resulted in the erection of several different nomenclatural schemes for the Upper Jurassic stages (Figure 4). Wimbledon in Cope et al. (1980) advocated the use of the Kimmeridgian and Portlandian sensu anglico in Britain and this recommendation is followed in this study. Most of the oil companies operating in the North Sea area, however, use the Kimmeridgian and Volgian stages, the latter based on condensed sequences on the Russian Platform.

APROX POSITION OF FIG. 4 →

Dinocyst assemblages in the Jurassic also show some degree of provincialism, although to a much lesser extent than the invertebrate groups. Similar microplankton assemblages are recorded from the Boreal and Tethyan realms during the Hettangian to Oxfordian, but in the Kimmeridgian and Portlandian, several species are confined to one or other of these two regions (Riding & Sarjeant 1985).

In many publications on European dinocyst stratigraphy the ranges of taxa are defined in terms of ammonite zones (Riding 1984). While reviewing the correlation of Jurassic rocks in Britain, Torrens in Cope et al. (1980) argued against this practice and recommended (p.12) "...a record of zonally significant forms plotted against a series of lithological divisions". However Woollam & Riding (1983) stated that the very refined biostratigraphy established from the study of ammonite faunas in the British Isles provides an ideal reference for comparison with any micropalaeontological zonation scheme. They also argued that ammonite zones have a very strong chronostratigraphic connotation and strata which contain no ammonite fauna are nevertheless frequently assigned to zones. This latter approach is followed in the present study, where ammonite zones are treated as informal chronozones. Dinocyst biostratigraphy is used to allocate ammonite "chronozones" to strata where ammonites are poorly preserved or lacking, for example, in the section from Helmsdale to Dùn Glas.

The stratigraphical distribution of the 51 dinocyst species recorded (Figure 5) reveals that approximately one third range through the whole or most of the section and consequently are of little use for biostratigraphical purposes. *Cribroperidinium* spp., *Cyclonephelium hystrix* and members of the *Adnatosphaeridium caulleryi* group are the most abundant forms. Other common, long ranging taxa include *Chytroeisphaeridia chytroeides*, *Escharisphaeridia pocockii*, *Pareodinia ceratophora*, *Sirmiodinium grossii*, *Systematophora areolata* and *Tubotuberella apatela*. Less common long ranging taxa include *Chlamydophorella* sp., *Cleistosphaeridium polyacanthum* and *Glossodinium dimorphum*. The rarity of *G. dimorphum* is unusual considering it is one of the commoner elements in most European assemblages (Riding 1984). Among the short ranging, biostratigraphically useful dinocysts are *Cribroperidinium longicorne*, *Dichadogonyaulax*? *pannea*, *Dingodinium tuberosum*, *Egmontodinium expiratum*, *Kleithriasphaeridium porosispinum*, *Gochteodinia mutabilis*, *Muderongia* sp.A Davey 1979, *Occisucysta balia* and *Senoniasphaera jurassica*. These taxa have range bases or tops within the Kimmeridgian and are readily identifiable.

APROX POSITION OF FIG 5 →

***cymodoce* and *mutabilis* ammonite zones**: Common species within these zones include *Sentusidinium echinatum*, *S. sparsibarbatum*, *Systematophora areolata*, *S. penicillata* and *Tubotuberella apatela*. Taxa appearing in the *mutabilis* ammonite Zone include *Dichadogonyaulax*? *pannea*, *Hystrichodinium pulchrum*, *Leptodinium eumorphum* and

Cribroperidinium longicorne. Lam & Porter (1977) also recorded the inception of D? pannea within this zone, though it is not seen until the wheatleyensis ammonite Zone in the type Kimmeridgian section in Dorset (Riding, unpublished data). Cleistosphaeridium tribuliferum and Sentusidinium pilosum are found only within these two zones in the present study.

eudoxus and autissiodorensis ammonite zones: Systematophora penicillata is still abundant and Dingodinium tuberosum becomes increasingly common in these two zones. Numbers of Cribroperidinium longicorne increase in the autissiodorensis ammonite Zone. Incoming taxa include Cribroperidinium globatum, C. granuligerum, Oligosphaeridium pulcherrimum sensu Ioannides et al. 1977 in the eudoxus ammonite zone and Occisucysta balia and Senoniasphaera jurassica in the autissiodorensis ammonite Zone. A eudoxus ammonite Zone inception for O. pulcherrimum sensu Ioannides et al. 1977 was also noted by Riding (unpublished data) in the type Kimmeridgian section. Subtilisphaera? inaffecta is not seen above the eudoxus ammonite Zone and Gonyaulacysta jurassica last appears in the autissiodorensis ammonite Zone. Both species are very rare in this section.

elegans and scitulus ammonite zones: Dinocyst assemblages in these zones are similar to those in the eudoxus and autissiodorensis ammonite zones. Cribroperidinium spp. become increasingly abundant in the scitulus ammonite Zone and Systematophora penicillata is rare in both zones. No species inceptions or extinctions are recorded from the elegans ammonite Zone, but first appearances of Cribroperidinium sp.A Davey 1982a, Perisseiasphaeridium sp. and Prolixosphaeridium capitatum are noted in the scitulus ammonite Zone. Davey (1982a) recorded that Cribroperidinium sp.A was most abundant in the Lower Portlandian of his sections; the occurrence here in the late Kimmeridgian represents an extension to that range. Cribroperidinium longicorne reaches its acme in the scitulus ammonite Zone, with a flood of specimens occurring in sample 76, near the base of the zone.

wheatleyensis and hudlestoni ammonite zones: Species of the Adnatosphaeridium caulleryi group are more common here than in previous zones, as are Chytroeisphaeridia chytroeides, Dingodinium tuberosum and Escharisphaeridia pocockii. Gochteodinia mutabilis first appears in the wheatleyensis ammonite Zone, though Riley, in Fisher & Riley (1980), noted a pectinatus ammonite Zone inception for this species in the sections he examined in northwest Europe. Systematophora penicillata, Oligosphaeridium pulcherrimum sensu Ioannides et al. 1977 and Perisseiasphaeridium sp. have their range tops in the wheatleyensis ammonite Zone. A flood of Senoniasphaera jurassica specimens was noted in sample 87, at the top of the wheatleyensis ammonite Zone.

pectinatus to albani ammonite zones: Using published ranges for several dinocyst taxa, an attempt was made to define ammonite zonal boundaries within the pectinatus to albani ammonite zones. Linsley (1972) was unable to allocate this section to specific ammonite zones due to the lack of well preserved material. As the number of known dinocyst species range bases and tops within these five ammonite zones is limited, only two zonal boundaries could be recognized for this part of the section, namely the Pavlovia pallasioides/

rotunda and the Virgatopavlovia fittoni/albani zonal boundaries, the latter also coinciding with the Kimmeridgian/Portlandian stage boundary. Riding (1984) placed the range base of Muderongia sp.A Davey 1979 at the base of the rotunda ammonite Zone, which in this study is between samples 93 and 95. Dingodinium tuberosum and Occisucysta balia become extinct at the top of the fittoni ammonite Zone according to Woollam & Riding (1983), which is taken to be between sample 102 and 103 at Dùn Glas. This confirms Riley's (1980) suggestion that the youngest sediments exposed are early Portlandian in age.

The richest assemblages of dinocysts are encountered in the rotunda to fittoni ammonite zones, where abundant Adnatosphaeridium caulleryi group species, Cribroperidinium spp., Cyclonephelium hystrix, Dichadogonyaulax? pannea, Hystrichodinium pulchrum and Muderongia sp.A Davey 1979 are found. Less abundant, though still common, are Escharisphaeridia pocockii and Sirmiodinium grossii. New taxa appearing for the first time in the rotunda- fittoni ammonite zones include Cassiculosphaeridia magna, Egmontodinium expiratum, E. polyplacophorum, Hystrichosphaeridium petilum, Kleithriasphaeridium porosispinum and Leptodinium antigonium. In the type Kimmeridgian section, E. expiratum first appears in the hudlestoni ammonite Zone (Riding, unpublished data) and Davey (1982a) recorded a pectinatus ammonite Zone inception for K. porosispinum in Dorset and eastern England. The apparent later appearance of both taxa at Helmsdale is probably due to their rarity in the present study. Cribroperidinium longicorne is last seen in the rotunda-fittoni ammonite zones, which is unusual and may be due to reworking as hudlestoni and pallasioides ammonite Zone range tops were recorded by Riding (unpublished data) and Raynaud (1978) respectively. The occurrences of Gonyaulacysta eisenackii, Rhynchodiniopsis cladophora and R. nealei are also presumed to be due to reworking as all have predominantly Oxfordian ranges in the literature. One specimen of Muderongia simplex is recorded here; previous records indicate an early Cretaceous age (Woollam & Riding 1983; Davey 1982a).

The assemblage recorded from the albani ammonite Zone is relatively rich in dinocysts, though the number of species is reduced compared to those recorded in the rotunda - fittoni ammonite zones. The A. caulleryi group, Cribroperidinium spp., C. hystrix, D? pannea and Muderongia sp.A Davey 1979 are all abundant in the albani ammonite Zone. Similar assemblages are reported in the Ctenidodinium culmulum-C.panneum (Cc/Cp) dinocyst Zone of Woollam & Riding (1983) which is equivalent to the albani - Glaucolithites glaucolithus ammonite Zone.

BIOSTRATIGRAPHIC SUMMARY AND COMPARISON WITH PREVIOUS ZONATION SCHEMES

Dinocysts confined to the Lower Kimmeridgian of Helmsdale include Gonyaulacysta jurassica, Sentusidinium pilosum, Subtilisphaera? inaffecta and Systematophora penicillata. Many of the taxa present in the Lower Kimmeridgian also range into the Upper Kimmeridgian and basal Portlandian, where Cribroperidinium sp.A Davey 1982a, Dichadogonyaulax? pannea, Egmontodinium polyplacophorum, E. expiratum, Gochteodinia mutabilis, Hystrichodinium pulchrum, Muderongia sp.A Davey 1979, Senoniasphaera jurassica and Sirmiodinium grossii are distinctive forms.

The flood of Cribroperidinium longicorne in the scitulus ammonite Zone and S. jurassica in the wheatleyensis ammonite Zone could prove useful stratigraphic markers in the local area and possibly further afield.

Although the majority of the dinocysts are damaged and poorly preserved, most are considered to be indigenous. There is, however, some evidence of reworking from the records of G. eisenackii, R. cladophora, R. nealei, the extended range of C. longicorne and the presence of Devonian and Carboniferous miospores (Lam & Porter 1977; Riley 1980).

The most comprehensive Jurassic dinocyst zonation scheme to date is that of Woollam & Riding (1983) in which 16 dinocyst zones and 29 subzones were recognized, all of which were related to the standard ammonite zonation. The top of the Scriniodinium luridum dinocyst Zone of Woollam & Riding (1983) is based on the extinction of S. luridum, a species not found in the present study. The overlying zone, the Glossodinium dimorphum - Dingodinium tuberosum (Gd/ Dt) dinocyst Zone is divided into three subzones, based on the appearance of E. polyplacophorum and the extinctions of G. jurassica and D. tuberosum. Due to the lack of overlap between the ranges of E. polyplacophorum and G. jurassica in the present study, none of these subzones could be distinguished. However, the extinction of D. tuberosum and Occisucysta balia enabled the rcognition of the boudary between the Gd/Dt and the Cc/Cp dinocyst zones of Woollam & Riding (1983), which also marks the fittoni/albani ammonite Zone boundary. The assemmblage from sample 103 probably represents subzone a of the Cc/Cp dinocyst Zone, despite the absence of S. jurassica, the extinction of which marks the top of this subzone. This confirms the suggestion of Riley (1980) of an Early Portlandian age for the youngest samples exposed at Dùn Glas. The pallasioides/rotunda ammonite Zone boundary is marked by the appearance of Muderongia sp.A Davey 1979 in sample 95.

PALYNOMORPH DISTRIBUTION AND PALAEOENVIRONMENTS

Palynomorph assemblages of early Kimmeridgian age are dominated by miospores, including trilete spores, bisaccate pollen and other gymnospermous pollen such as Callialasporites, Cerebropollenites and Classopollis, which account for between 58 and 94% of the total palynomorphs recorded, with a mean of 73% (Figure 6). Terrestrially derived organic matter such as inertinite, vitrinite, cellular tissue and cuticle is more abundant than organic matter of marine origin such as algal sapropel. The removal of much of the fine detritus and amorphous matter during oxidation and ultrasonic treatment further supports this observation as terriginous organic matter is more easily removed by these means than that of marine origin (Batten 1981, 1983)

AΡROX POSITION OF FIG. 6 →

The Upper Kimmeridgian and lowermost Portlandian assemblages have greater fluctuations in the microplankton/miospore ratio, though there is an increasing dominance of dinocysts and acritarchs in the scitulus, wheatleyensis and rotunda to albani ammonite zones. Included with the acritarchs are probable prasinophycean algae such as Crassosphaera, Pterospermella and Tasmanites. Miospores, though less abundant, still average 55% of the total palynomorphs. Kerogen compositions are similar to those of the Lower Kimmeridgian, though a decline in plant derived detritus is observed with a corresponding increase in amorphous material of presumed marine algal origin, especially in the rotunda to albani ammonite zones.

The presence of both microplankton and miospores in the preparations studied indicates deposition in a marine environment relatively close to a landmass from which fluvial discharge acted as a source of terrigenous material. Most of the samples collected came from black shales, which were probably deposited by suspension fall-out sedimentation in a hemipelagic environment. Slow rates of deposition are suggested by the well preserved ammonites and plant fragments (Pickering 1984).

Dinocyst diversity (Figure 6) is at a maximum in the mutabilis ammonite Zone and declines to about half in the rotunda to albani ammonite zones, despite the increase in dinocyst abundance. This is a probable reflection of the decline in total number of dinocyst species reported from the Kimmeridgian to the Portlandian worldwide (Bujak & Williams 1979)

Reactivation of the Helmsdale Fault, initiated at the beginning of the Early Kimmeridgian caused increased subsidence and basin deepening to occur (MacDonald 1985). The resultant changes in the width and composition of the submarine shelf has affected palynomorph composition throughout the Kimmeridgian and basal Portlandian (Figure 6). During the Early Kimmeridgian this basin deepening was associated with the transition from relatively oxic to probable anoxic bottom conditions, leading to decreased microbial activity and thus allowing the better preservation of dinocysts observed in the upper part of the section. Restricted water circulation and rises in sea level caused widespread stagnant conditions throughout northwest Europe during the Kimmeridgian (Tyson et al. 1979).

During cymodoce and mutabilis ammonite zone times the submarine shelf was narrow and relatively sandy, with evidence of limited wave reworking on the slope in the cymodoce ammonite Zone indicating the basin was still relatively shallow and above wave base at times (MacDonald 1985). The general lack of sapropelic kerogen and the poor dinocyst preservation suggests oxic, relatively high-energy bottom conditions. By mutabilis ammonite Zone times the basin was entirely below wave base. Abundant syn-sedimentary deformation at Kintradwell suggests that the sedimentary pile was oversteepened by rapid basin subsidence. By the eudoxus ammonite Zone MacDonald (1985) suggested a wider, less sandy shelf was present, and from the autissiodorensis ammonite Zone to the Early Portlandian, a wide, sediment-starved shelf existed. The reduction in the sediment content on the shallow shelf allowed the development of coral reefs, the remains of which are seen as clasts in the boulder beds (Neves & Selley 1975; MacDonald 1985).

The composition of the palynomorph assemblages and kerogen types broadly supports the palaeoenvironmental interpretation of MacDonald (1985), with the abundance of miospores and terrigenous debris suggesting that a shoreline with sources of fluvial discharge was close to the depositional site located on the basin side of the fault (Figure 7). Decreasing numbers of miospores and amounts of terrigenous detritus from the late Kimmeridgian supports the contention of a widening shelf area and increasing distance of the depositional site from the shoreline. The larger recovery of dinocysts in the Upper Kimmeridgian and lowermost Portlandian probably reflects a slower deposition rate (Davey 1982b), resulting from the decreased sediment load being deposited on the slope after transportation over the wider shelf, and to the greater

APPROX. POSITION OF FIG. 7 →

liklehood of preservation in a more anoxic environment.

Above the wheatleyensis ammonite Zone the miospore composition of the assemblages is seen to change with an increase in gymnospermous pollen and a corresponding decrease in trilete spore numbers. This may be a reflection of an increase in the gymosperm and a decrease in the pteridophyte component of the flora, due possibly to a climatic change, although there is no geological evidence to support this conclusion. A more likely reason is that bisaccate pollen were generally lighter and more easily transported, and thus more likely to be found further from the shoreline or river effluence (Davey 1982b). This would also apply to small, thin-walled spores (Batten 1973).

Rawson & Riley (1982) proposed that the widespread regression which occurred during the middle of the of the Late Kimmeridgian of the North Sea area was eustatically controlled, and was never completely masked by local tectonics. MacDonald (pers. comm.) found no sedimentological evidence at Helmsdale for this regression and assumed movements of the Helmsdale Fault completely masked the regional sea level trend. The microplankton/ miospore ratio during the pectinatus and pallasioides ammonite zones (Figure 6), however, shows a marked decline in actual and relative dinocyst abundance, possibly reflecting this Late Kimmeridgian regression of Rawson & Riley (1982). If this assumption is correct, Kimmeridgian palynomorph assemblage trends of the Helmsdale region would appear to be more sensitve indicators of sea-level fluctuations than the sedimentological evidence.

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Fig. 1 Geological map of the Brora - Helmsdale area. Modified after Pickering (1984), MacDonald (1985) and BGS one inch sheet 103.

Fig. 2 Ammonite zonation of the Upper Jurassic of east Sutherland. The cymodoce to the base of the elegans ammonite Zone is based on ammonite data of Linsley (1972), while the base and top of the scitulus and hudlestoni ammonite zones are based on structural reinterpretation of Linsley's (1972) ammonite zones by MacDonald (1985). The base of the rotunda and the top of the fittoni ammonite zones are based on the present work.

Fig. 3 Lithostratigraphy and biostratigraphy of the Upper Jurassic section. Derivation of ammonite zonation as for fig. 2.

Fig. 4 Upper Jurassic stage nomenclature. Adapted from Riley (1977), Davey (1979) and Cope et al. (1980).

Fig. 5 Stratigraphic ranges of dinocysts in the Upper Jurassic of east Sutherland. Derivation of ammonite zonation as for fig. 2.

Fig. 6 Palynomorph ratio, dinocyst diversity and composition and abundance logs from the Upper Jurassic of east Sutherland. Derivation of ammonite zonation as for fig. 2.

Fig. 7 Depositional model of the Upper Jurassic boulder beds and associated deposits around Helmsdale. Adapted from Trewin (1984) and Pickering (1984).

PLATE 1

All specimens are from the Helmsdale Boulder Beds.

All figures x500.

Fig.1. - Cribroperidinium longicorne (Downie 1957) Lentin & Williams 1985. MCP 3818/3. Sample 97, rotunda-fittoni ammonite zones. Note the thin wall and faint paratabulation.

Figs.2,3.- Cribroperidinium sp.A Davey 1982a. MCP 3701/7. Sample 76, scitulus ammonite Zone. 2. Detail of apical horn, which is hollow for approximately half its length. Note antapical ornament. 3. Medial view, showing paratabulation.

Fig.4. - Cribroperidinium sp. MCP 3713/6. Sample 102, rotunda-fittoni ammonite zones. Specimen with prominent apical horn and antapical spines. Composite photomicrograph.

Fig.5. - Cribroperidinium sp. MCP 3713/4. Sample 102, rotunda-fittoni ammonite zones. Specimen with prominent, irregular spines.

Fig.6. - Dichadogonyaulax? pannea (Norris 1965) Sarjeant 1969. MCP 3712/5. Sample 100, rotunda-fittoni ammonite zones. Oblique antapical view.

Fig.7. - Cyclonephelium hystrix (Eisenack 1958) Davey 1978. MCP 3712/5. Sample 100, rotunda- fittoni ammonite zones. Note distinct offset antapical bulge and bald central portion. Operculum still attached.

Fig.8. - Dingodinium tuberosum (Gitmez 1970) Riley in Fisher & Riley 1980. MCP 3713/6. Sample 102, rotunda-fittoni ammonite zones. Apical archaeopyle, operculum in place.

Fig.9. - Egmontodinium expiratum Davey 1982a. MCP 3819/3. Sample 103, albani ammonite Zone. Note processes formed from extensions of the parasutural crests. Composite photomicrograph.

Fig.10.- Egmontodinium polyplacophorum Gitmez & Sarjeant 1972. MCP 3819/3. Sample 103, albani ammonite Zone. Specimen with prominent parasutural crests.

PLATE 2

All specimens are from the Helmsdale Boulder Beds.

All figures x500.

Fig.1. - Glossodinium dimorphum Ioannides et al. 1977. MCP 3818/5. Sample 97, rotunda- fittoni ammonite zones. Note prominent digitate antapical process.

Fig.2. - Oligosphaeridium pulcherrimum (Deflandre & Cookson 1955) Davey & Williams 1966 sensu Ioannides et al. 1977. MCP 3703/4. Sample 80, scitulus ammonite Zone. Note the distally expanded fenestrate processes. Composite photomicrograph.

Fig.3. - Gochteodinia mutabilis (Riley in Fisher & Riley 1980) Davey 1982a. MCP 3712/5. Sample 100, rotunda- fittoni ammonite zones. Note apicular structure.

Fig.4. - Leptodinium antigonium Ioannides et al. 1977. MCP 3818/4. Sample 97, rotunda- fittoni ammonite zones. Note denticulate antapical crest.

Fig.5. - Muderongia sp.A Davey 1979. MCP 3818/4. Sample 97, rotunda- fittoni ammonite zones. Note angular endocyst extending into proximal regions of antapical horns.

Fig.6. - Senoniasphaera jurassica (Gitmez & Sarjeant 1972) Lentin & Williams 1976. MCP 3712/5. Sample 100, rotunda- fittoni ammonite zones. Specimen with partly detached operculum.

Fig.7. - Occisucysta balia Gitmez 1970. MCP 3713/4. Sample 102, rotunda- fittoni ammonite zones.

Figs.8,9.- Muderongia simplex Alberti 1961. MCP 3712/5. Sample 100, rotunda- fittoni ammonite zones. Specimen showing subspherical endocyst and detached operculum. 8. Low focus. 9. High focus.

Fig.10. - Perisseiasphaeridium sp. Davey 1982a. MCP 3706/5. Sample 87, wheatleyensis ammonite Zone.

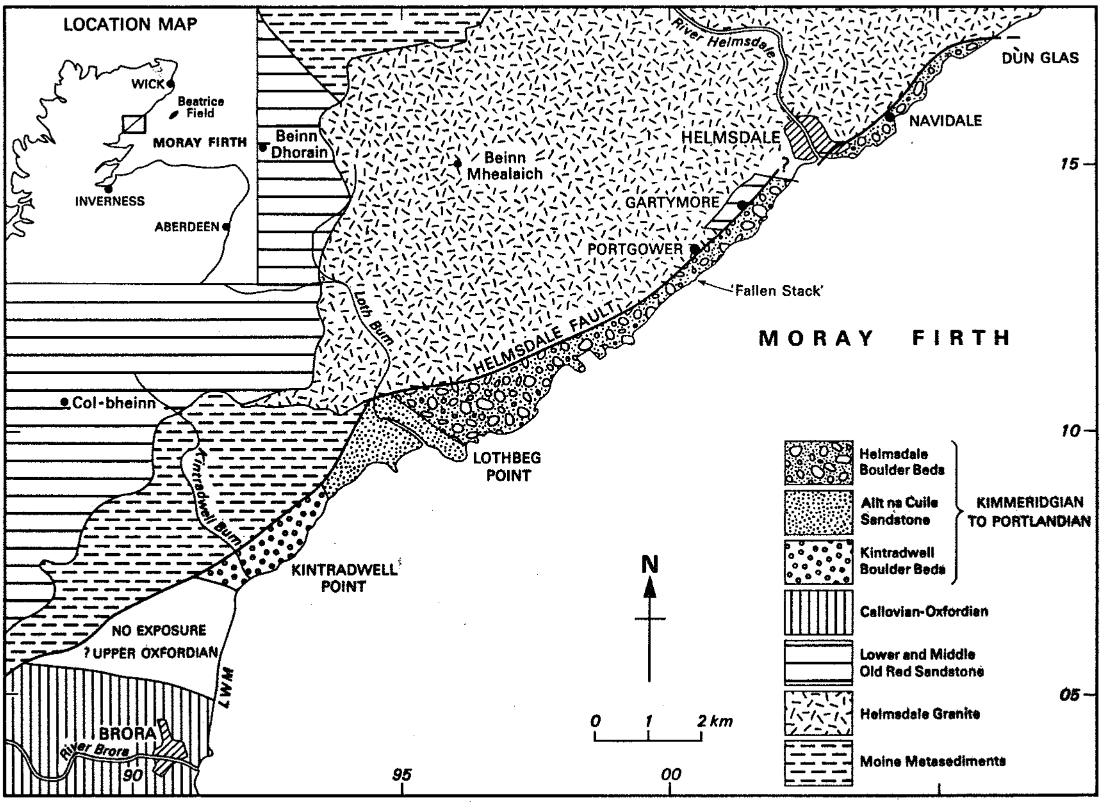

LOCATION MAP
WICK
Beatrice Field
MORAY FIRTH
INVERNESS
ABERDEEN
Beinn Dhorain
Beinn Mhealaich
River Helmsdale
HELMSDALE
DÙN GLAS
NAVIDALE
GARTYMORE
PORTGOWER
'Fallen Stack'
HELMSDALE FAULT
MORAY FIRTH
Loth Burn
Col-bheinn
LOTHBEG POINT
Kintradwell Burn
KINTRADWELL POINT
NO EXPOSURE
? UPPER OXFORDIAN
HWM
BRORA
River Brora
90
95
00
15
10
05
N
0 1 2 km
Helmsdale Boulder Beds
Allt na Cuile Sandstone
Kintradwell Boulder Beds
KIMMERIDGIAN TO PORTLANDIAN
Callovian-Oxfordian
Lower and Middle Old Red Sandstone
Helmsdale Granite
Moine Metasediments

FIG 1

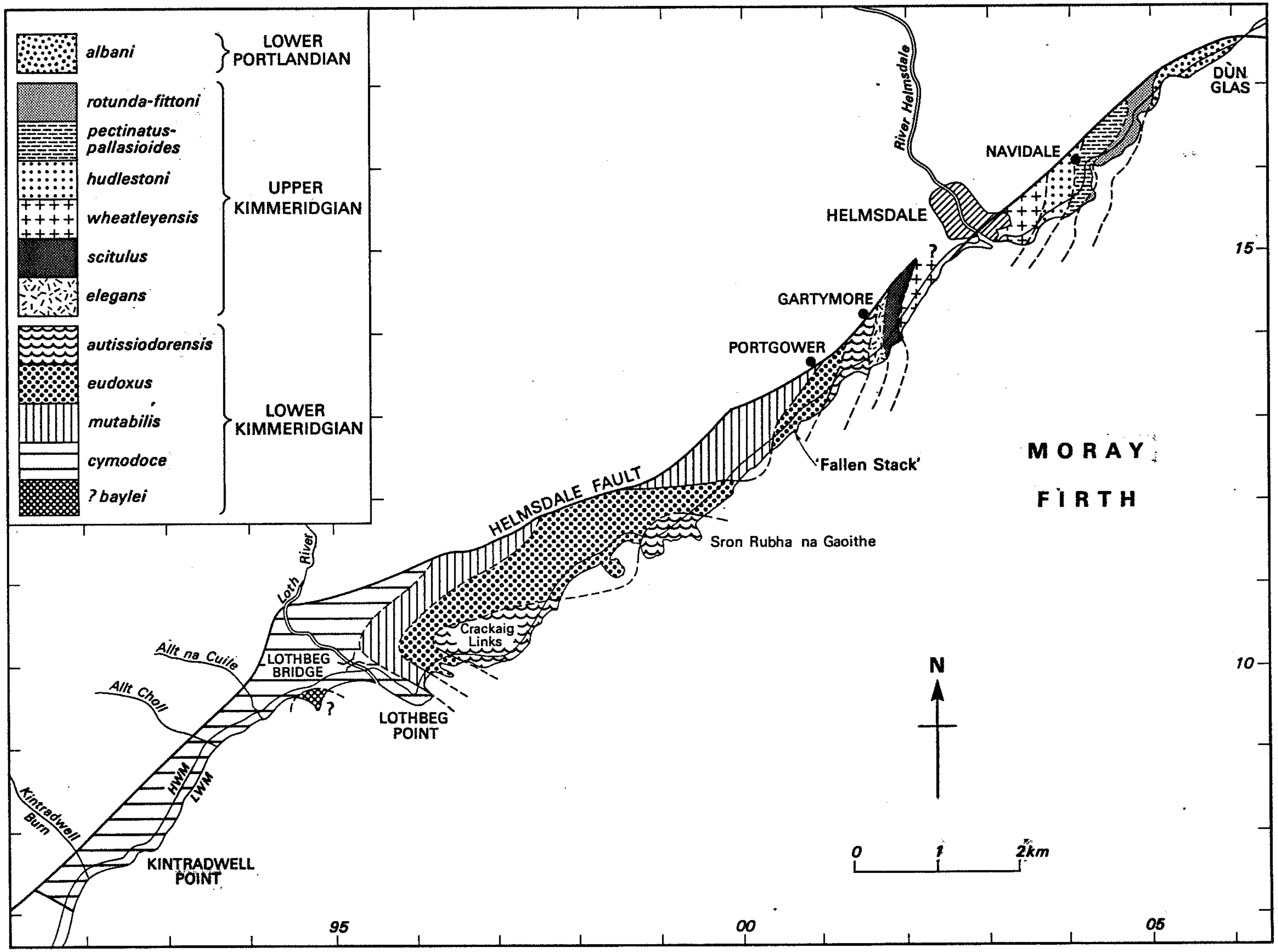
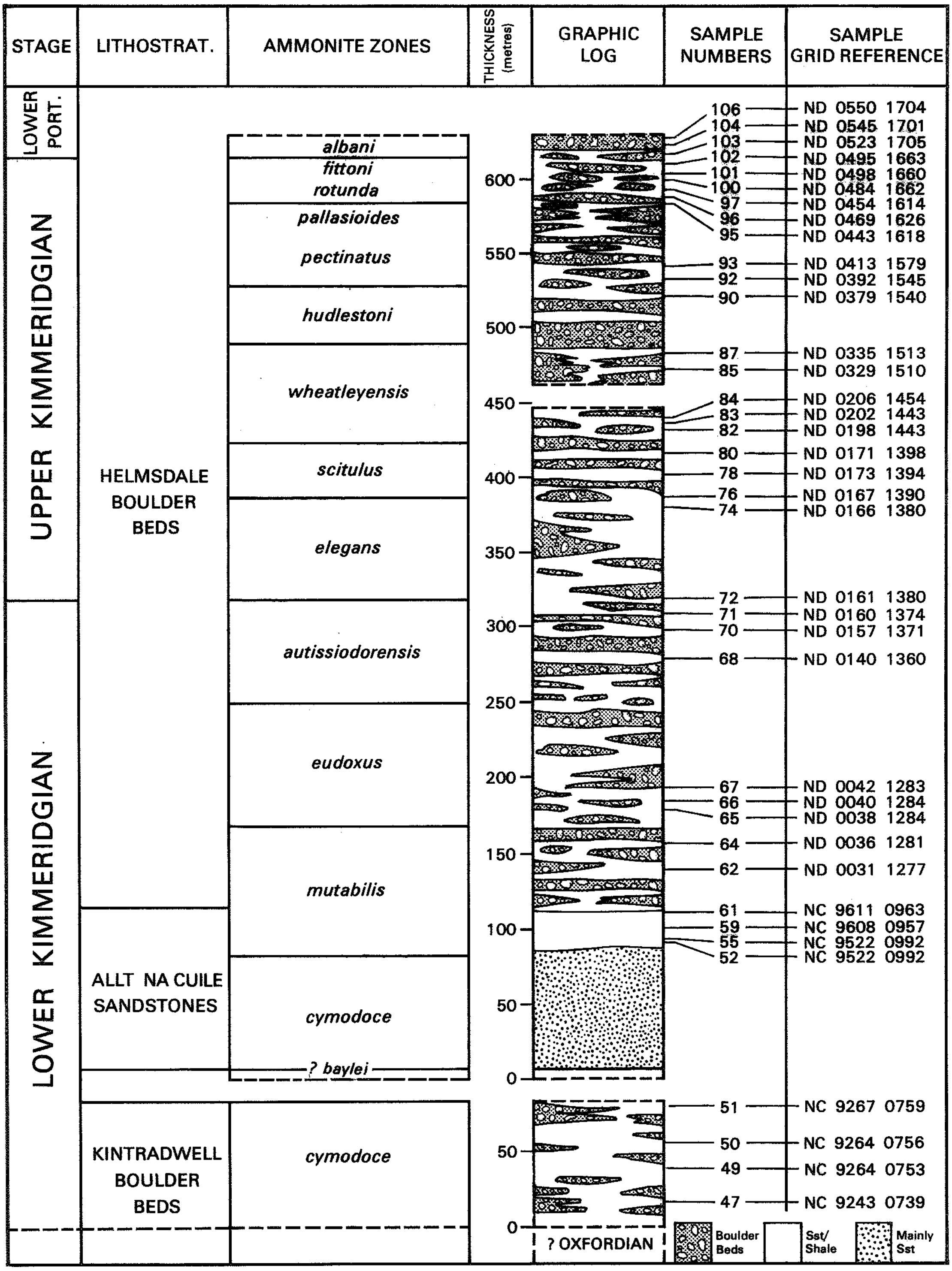

albani
LOWER PORTLANDIAN
rotunda-fittoni
pectinatus-pallasioides
hudlestoni
wheatleyensis
scitulus
elegans
UPPER KIMMERIDGIAN
autissiodorensis
eudoxus
mutabilis
cymodoce
? baylei
LOWER KIMMERIDGIAN
River Helmsdale
DÙN GLAS
NAVIDALE
HELMSDALE
GARTYMORE
PORTGOWER
'Fallen Stack'
MORAY
FIRTH
HELMSDALE FAULT
Sron Rubha na Gaoithe
Crackaig Links
Loth River
Allt na Cuile
Allt Choll
LOTHBEG BRIDGE
LOTHBEG POINT
Kintradwell Burn
HWM
LWM
KINTRADWELL POINT
N
0
1
2km
15
10
95
00
05

FIG 2



STAGE
LITHOSTRAT.
AMMONITE ZONES
THICKNESS (metres)
GRAPHIC LOG
SAMPLE NUMBERS
SAMPLE GRID REFERENCE
LOWER PORT.
UPPER KIMMERIDGIAN
LOWER KIMMERIDGIAN
HELMSDALE BOULDER BEDS
ALLT NA CUILE SANDSTONES
KINTRADWELL BOULDER BEDS
albani
fittoni
rotunda
pallasioides
pectinatus
hudlestoni
wheatleyensis
scitulus
elegans
autissiodorensis
eudoxus
mutabilis
cymodoce
? baylei
cymodoce
600
550
500
450
400
350
300
250
200
150
100
50
0
50
0
? OXFORDIAN
106 ND 0550 1704
104 ND 0545 1701
103 ND 0523 1705
102 ND 0495 1663
101 ND 0498 1660
100 ND 0484 1662
97 ND 0454 1614
96 ND 0469 1626
95 ND 0443 1618
93 ND 0413 1579
92 ND 0392 1545
90 ND 0379 1540
87 ND 0335 1513
85 ND 0329 1510
84 ND 0206 1454
83 ND 0202 1443
82 ND 0198 1443
80 ND 0171 1398
78 ND 0173 1394
76 ND 0167 1390
74 ND 0166 1380
72 ND 0161 1380
71 ND 0160 1374
70 ND 0157 1371
68 ND 0140 1360
67 ND 0042 1283
66 ND 0040 1284
65 ND 0038 1284
64 ND 0036 1281
62 ND 0031 1277
61 NC 9611 0963
59 NC 9608 0957
55 NC 9522 0992
52 NC 9522 0992
51 NC 9267 0759
50 NC 9264 0756
49 NC 9264 0753
47 NC 9243 0739
Boulder Beds
Sst/ Shale
Mainly Sst

FIG 3

<table>
<tr><th rowspan="3"></th><th rowspan="3">STANDARD AMMONITE ZONES</th><th colspan="6">BOREAL PROVINCE</th><th rowspan="3">TETHYAN PROVINCE</th><th rowspan="3"></th></tr>
<tr><th colspan="3">N. W. EUROPE</th><th colspan="3" rowspan="2">RUSSIAN PLATFORM</th></tr>
<tr><th colspan="2">sensu anglico</th><th>sensu gallico</th></tr>
<tr><td rowspan="22">UPPER JURASSIC</td><td>lamplughi</td><td rowspan="9">PORTLANDIAN</td><td rowspan="3">UPPER</td><td rowspan="17">PORTLANDIAN</td><td colspan="2" rowspan="17">VOLGIAN</td><td rowspan="3">UPPER</td><td rowspan="3"></td><td rowspan="3">LOWER CRET.</td></tr>
<tr><td>preplicomphalus</td></tr>
<tr><td>primitivus</td></tr>
<tr><td>oppressus</td><td rowspan="6">LOWER</td><td rowspan="9">MIDDLE</td><td rowspan="14">? TITHONIAN</td><td rowspan="19">UPPER JURASSIC</td></tr>
<tr><td>anguliformis</td></tr>
<tr><td>kerberus</td></tr>
<tr><td>okusensis</td></tr>
<tr><td>glaucolithus</td></tr>
<tr><td>albani</td></tr>
<tr><td>fittoni</td><td rowspan="13">KIMMERIDGIAN</td><td rowspan="8">UPPER</td></tr>
<tr><td>rotunda</td></tr>
<tr><td>pallasioides</td></tr>
<tr><td>pectinatus</td><td rowspan="5">LOWER</td></tr>
<tr><td>hudlestoni</td></tr>
<tr><td>wheatleyensis</td></tr>
<tr><td>scitulus</td></tr>
<tr><td>elegans</td></tr>
<tr><td>autissiodorensis</td><td rowspan="5">LOWER</td><td rowspan="5">KIMMERIDGIAN</td><td colspan="3" rowspan="5">KIMMERIDGIAN</td><td rowspan="5">KIMMERIDGIAN</td></tr>
<tr><td>eudoxus</td></tr>
<tr><td>mutabilis</td></tr>
<tr><td>cymodoce</td></tr>
<tr><td>baylei</td></tr>
</table>

FIG 4

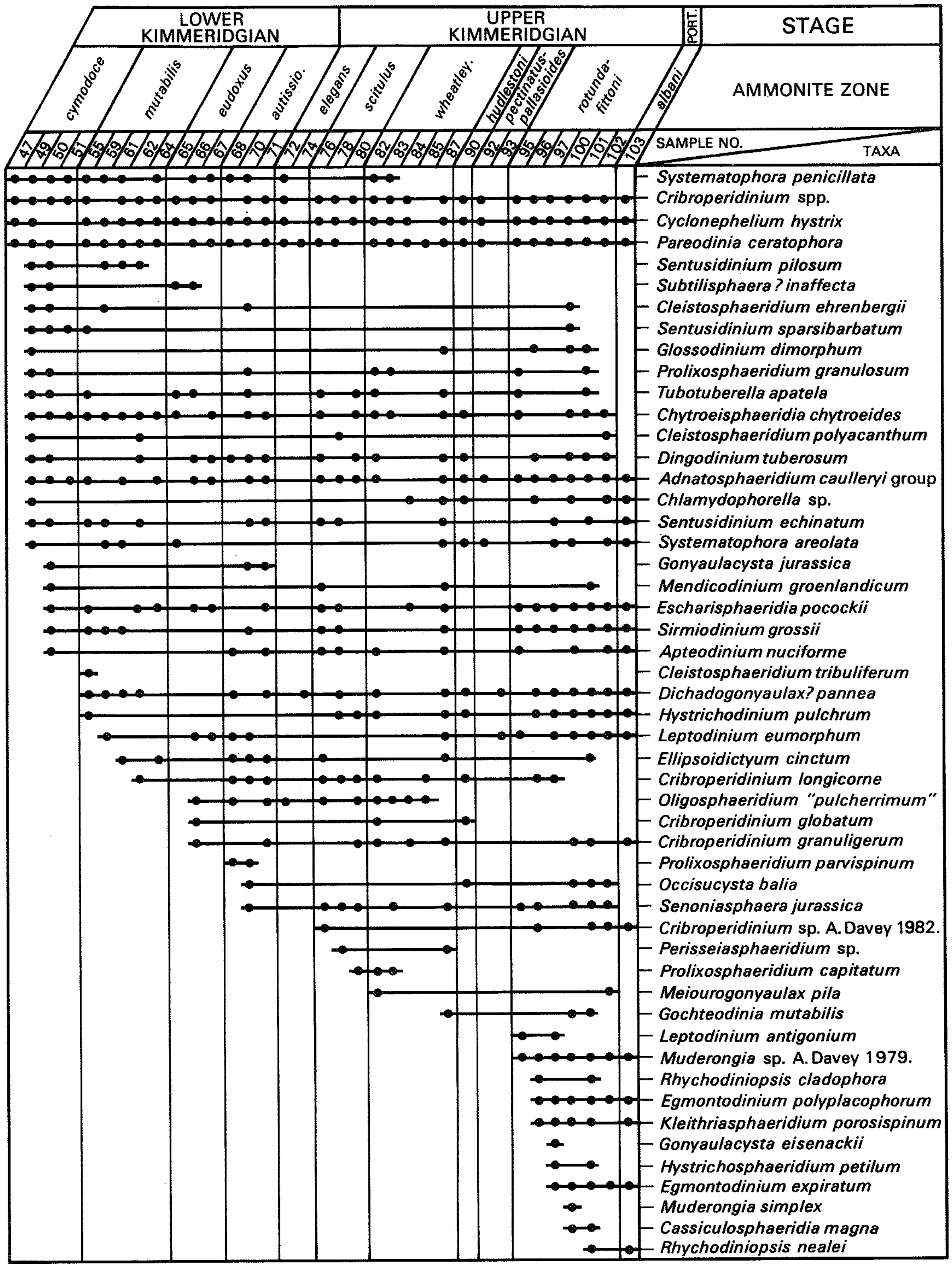

LOWER KIMMERIDGIAN
UPPER KIMMERIDGIAN
PORT.
STAGE
cymodoce
mutabilis
eudoxus
autissio.
elegans
scitulus
wheatleyi
hudlestoni
pectinatus-pallasioides
rotunda-fittoni
albani
AMMONITE ZONE
47
49
50
51
55
59
61
62
64
65
66
67
68
70
71
72
74
76
78
80
82
83
84
85
87
90
92
93
95
96
97
100
101
102
103
SAMPLE NO.
TAXA
Systematophora penicillata
Cribroperidinium spp.
Cyclonephelium hystrix
Pareodinia ceratophora
Sentusidinium pilosum
Subtilisphaera ? inaffecta
Cleistosphaeridium ehrenbergii
Sentusidinium sparsibarbatum
Glossodinium dimorphum
Prolixosphaeridium granulosum
Tubotuberella apatela
Chytroeisphaeridia chytroeides
Cleistosphaeridium polyacanthum
Dingodinium tuberosum
Adnatosphaeridium caulleryi group
Chlamydophorella sp.
Sentusidinium echinatum
Systematophora areolata
Gonyaulacysta jurassica
Mendicodinium groenlandicum
Escharisphaeridia pocockii
Sirmiodinium grossii
Apteodinium nuciforme
Cleistosphaeridium tribuliferum
Dichadogonyaulax? pannea
Hystrichodinium pulchrum
Leptodinium eumorphum
Ellipsoidictyum cinctum
Cribroperidinium longicorne
Oligosphaeridium "pulcherrimum"
Cribroperidinium globatum
Cribroperidinium granuligerum
Prolixosphaeridium parvispinum
Occisucysta balia
Senoniasphaera jurassica
Cribroperidinium sp. A. Davey 1982.
Perisseiasphaeridium sp.
Prolixosphaeridium capitatum
Meiourogonyaulax pila
Gochteodinia mutabilis
Leptodinium antigonium
Muderongia sp. A. Davey 1979.
Rhychodiniopsis cladophora
Egmontodinium polyplacophorum
Kleithriasphaeridium porosispinum
Gonyaulacysta eisenackii
Hystrichosphaeridium petilum
Egmontodinium expiratum
Muderongia simplex
Cassiculosphaeridia magna
Rhychodiniopsis nealei

FIG 5

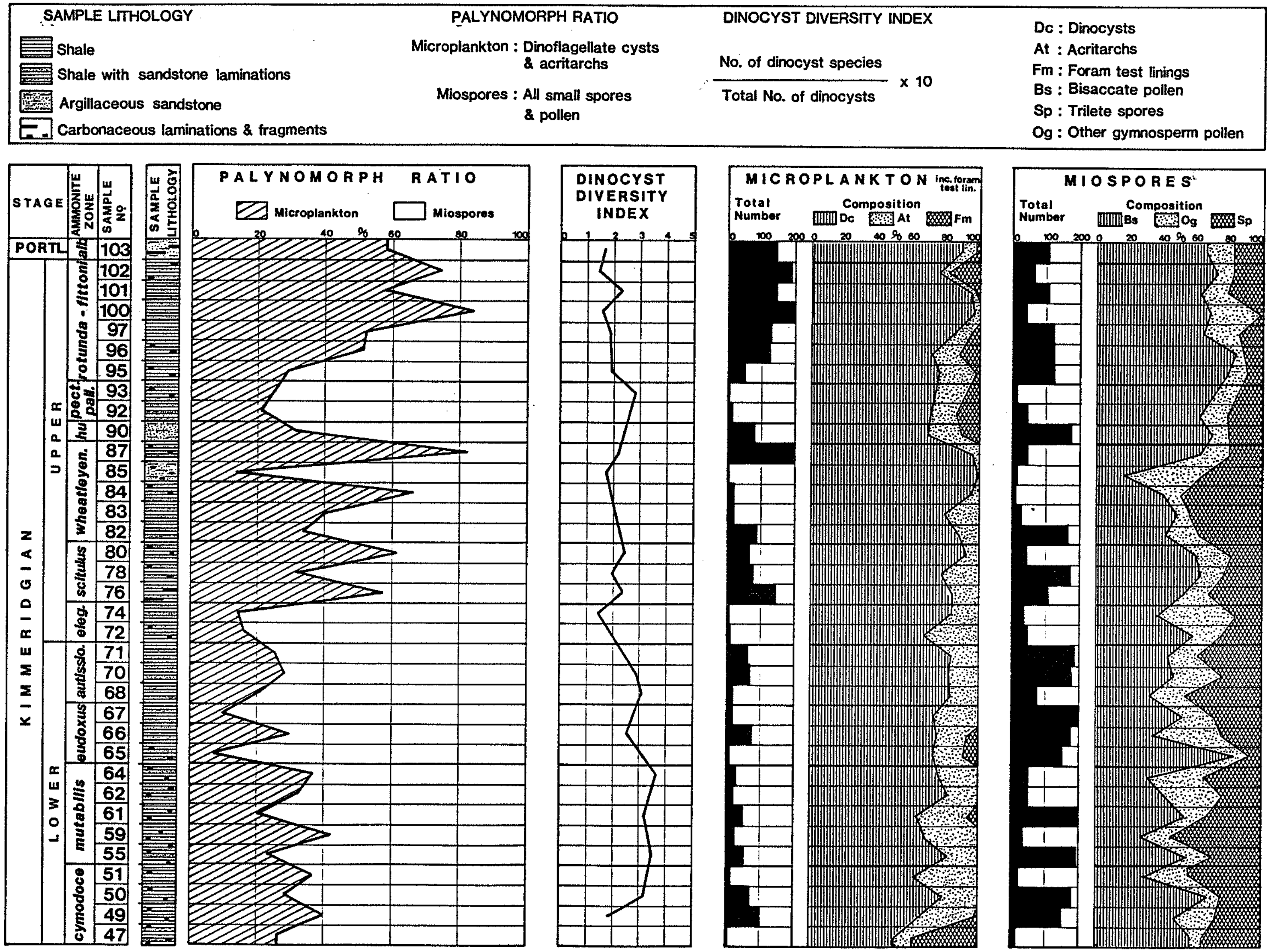
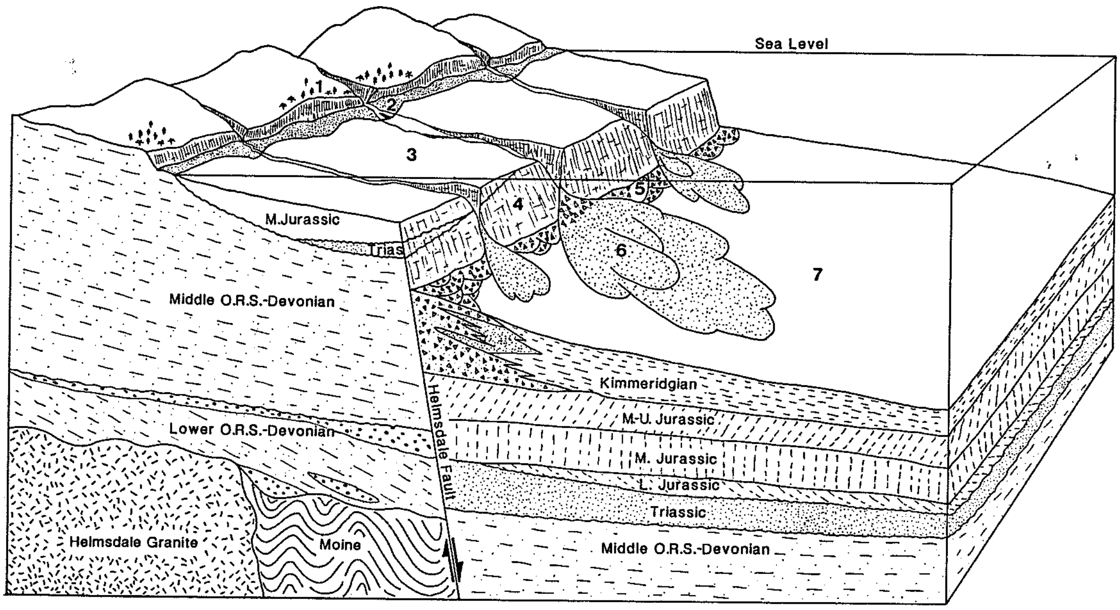

SAMPLE LITHOLOGY
Shale
Shale with sandstone laminations
Argillaceous sandstone
Carbonaceous laminations & fragments
PALYNOMORPH RATIO
Microplankton : Dinoflagellate cysts & acritarchs
Miospores : All small spores & pollen
DINOCYST DIVERSITY INDEX
No. of dinocyst species / Total No. of dinocysts x 10
Dc : Dinocysts
At : Acritarchs
Fm : Foram test linings
Bs : Bisaccate pollen
Sp : Trilete spores
Og : Other gymnosperm pollen
STAGE
AMMONITE ZONE
SAMPLE No
SAMPLE LITHOLOGY
PORTL.
KIMMERIDGIAN
UPPER
LOWER
alb.
rotunda - fittoni
pect. pall.
hu
wheatleyen.
scitulus
eleg.
autissio.
eudoxus
mutabilis
cymodoce
103
102
101
100
97
96
95
93
92
90
87
85
84
83
82
80
78
76
74
72
71
70
68
67
66
65
64
62
61
59
55
51
50
49
47
PALYNOMORPH RATIO
Microplankton
Miospores
DINOCYST DIVERSITY INDEX
MICROPLANKTON inc. foram test lin.
Total Number
Composition
Dc
At
Fm
MIOSPORES
Total Number
Composition
Bs
Og
Sp

FIG 6



1 Uplifting and eroding vegetated land area
2 Beach sand and gravel
3 Eroding shelf with abundant bioclastic debris
4 Active submarine fault scarp
5 Boulder beds from rockfall
6 Sand fans from gullies and canyons
7 Deep water anoxic shales

FIG. 7

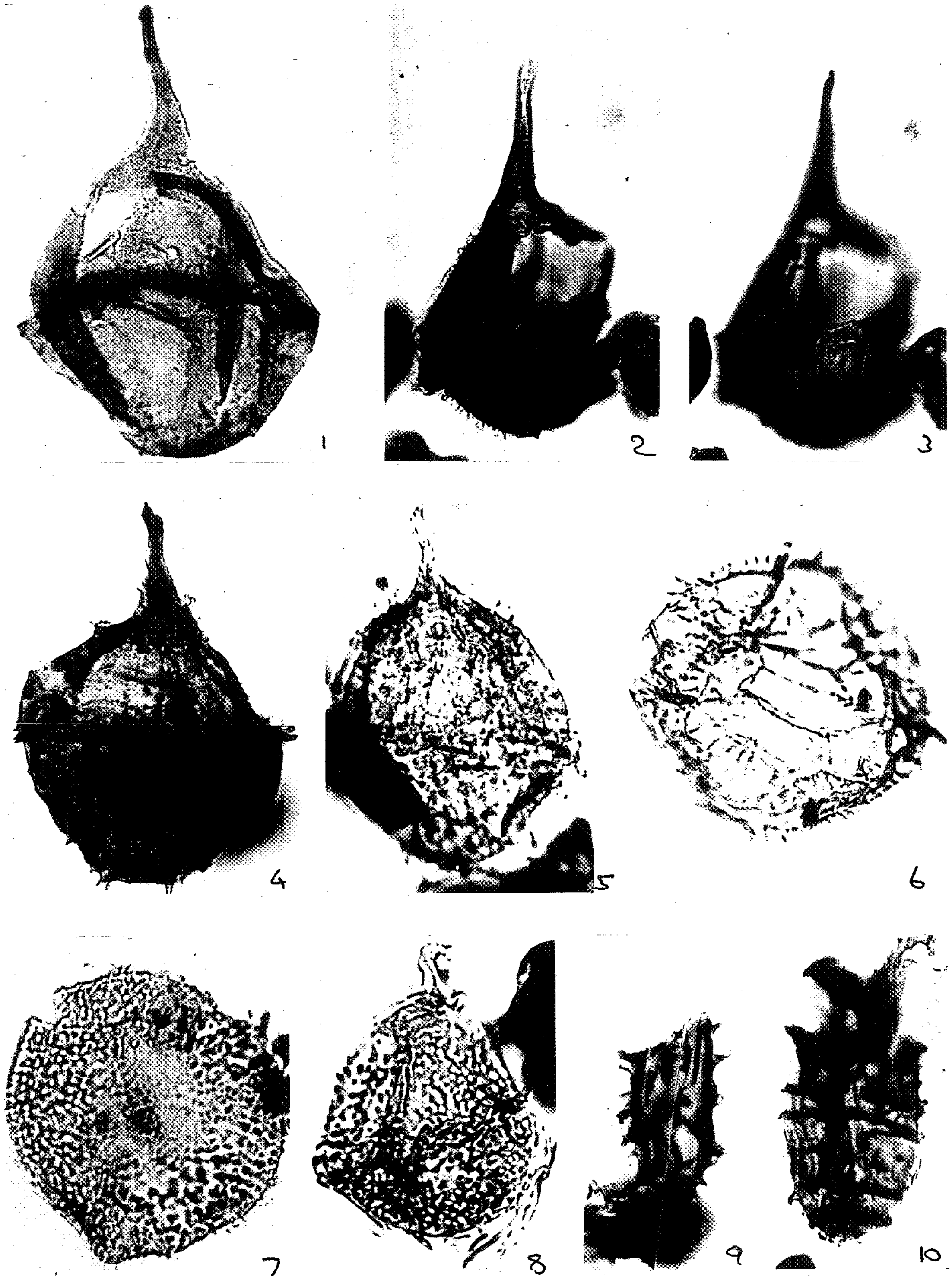


PLATE 1

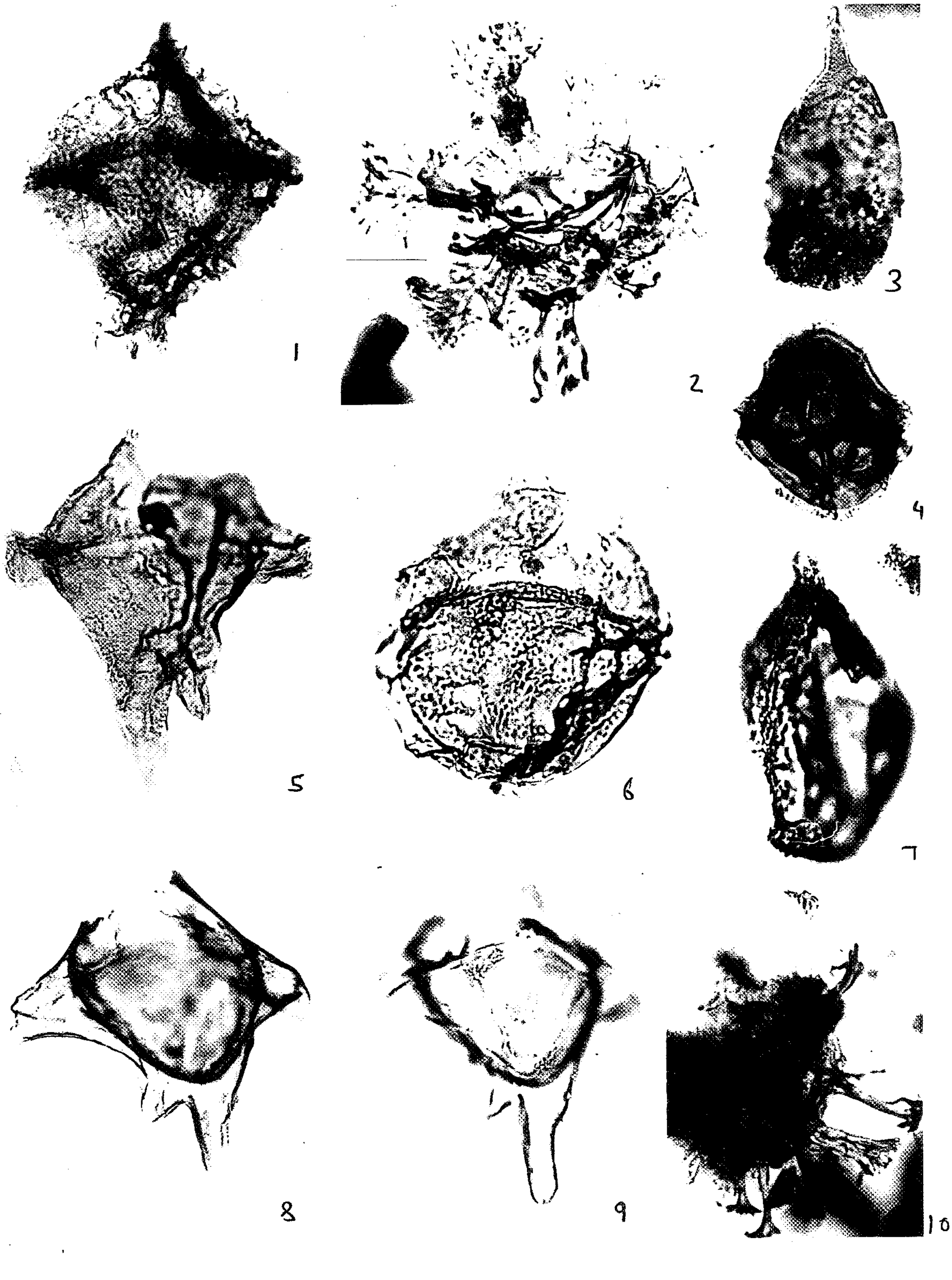


PLATE 2