LATE TRIASSIC, JURASSIC AND EARLY CRETACEOUS GEOLOGY OF THE SOUTHERN NORTH SEA BASIN

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Preface

Whereas the collection of much of the information presented in this thesis was undertaken by the author as a member of the Marine Geology Unit of the British Geological Survey, the author was solely responsible for the subsequent collation and interpretation of this and additional data including:

i) Compilation of the Jurassic isopach maps following reinterpretation of released commercial borehole data.

ii) The lithostratigraphic subdivision of the Late Triassic and Jurassic succession of the Southern North Sea Basin based upon a reinterpretation of the downhole geophysical log responses from these sequences.

iii) The thin section petrology, together with the preparation of all the mounted heavy mineral residues and the subsequent identification of the mineral grains.

iv) Logging of the cored boreholes and seabed samples referred to throughout this thesis, together with their lithostratigraphic interpretation.

v) Preparation of the geological map of the California Sheet presented as part of this thesis, based upon the geological interpretation of shallow seismic Sparker and Airgun data, together with the collation and interpretation of all the core and sample data available from the area.

During the logging of the boreholes their macrofaunas, together with subsamples for micropalaeontological examination, were collected by the author for subsequent identification by members of the

Palaeontology Unit of the B.G.S. Due acknowledgement for these identifications is given in the relevant parts of the thesis. The compilation of the biostratigraphy of the cored sequences was carried out by the author in consultation with colleagues of the Palaeontological Unit of the B.G.S. In particular, collaboration with Dr. Beris Cox and Dr. Brian Fletcher and Mr. Ian Wilkinson regarding the biostratigraphy of the cored Kimmeridgian and Speeton Clay sequences respectively is acknowledged.

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My supervisor Dr. J. D. Hudson has read and commented on many aspects of the thesis and has from his own research provided a stimulating example to follow.

Finally without the constant support of my wife Beryl, who has over several years had to contend not only with a growing family but also with a husband who has spent large portions of the summer months away at sea, I am sure that I would not even have come near completing this research project.

This thesis is dedicated to the memory of my brother Stephen.

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G.K.Lott, K. C.Ball and I.P.Wilkinson.
Proc.Yorks.Geol.Soc. 45 (4), pp.235-248,1985.

ENCLOSURE 4 (bound in the back of this thesis)
The stratigraphy of the Lower Cretaceous Speeton Clay Formation, from a cored borehole off the coast of north-east England.
G.K.Lott, B.N.Fletcher and I.P.Wilkinson.
Proc.Yorks.Geol.Soc. (in press).

ENCLOSURE 5 (bound in the back of this thesis)
Upper Jurassic stratigraphy of four shallow cored boreholes in the northern part of the Southern North Sea Basin (Blocks 42 and 47).
B.M.Cox, G.K.Lott, J.E.Thomas and I.P.Wilkinson.
Proc.Yorks.Geol.Soc.(in press).

CHAPTER 1

Introduction

1.1. Introduction

The primary aim of this thesis is to provide a comprehensive assessment of the geology of the Southern North Sea Basin during the Jurassic and Early Cretaceous. In order to achieve this the integration of a wide variety of data has been undertaken, including the interpretation of shallow seismic profiles, downhole geophysical log correlation and petrographic descriptions of all available core and seabed sample information from the offshore area. A number of onshore cored borehole sequences were examined in some detail to establish some control points with which to compare the largely uncored offshore successions.

For the purpose of this study the Southern North Sea Basin is defined as comprising that area of the U.K. continental shelf south of the line of latitude 55^{O}N i.e. south of the Mid-North Sea High (Figure 1.1) and west of line of longitude 3^{O}E i.e. west of the Cleaver Bank Uplift. The southern boundary of the basin is marked by the Anglo-Brabant High at about 53^{O}N, while its effective western margin, at least during the Middle Jurassic to Early Cretaceous, stretched only marginally beyond the present outcrop limits. In the south-west links with the southern England Basin were intermittently maintained throughout the Jurassic and Early Cretaceous (Ziegler 1982).

1.2. Methods

Shallow seismic data collected by the British Geological Survey (BGS) since 1979 in the U. K. sector of the Southern North Sea Basin have proved particularly useful in determining the present-day structure and outcrop patterns of the Mesozoic and Tertiary sequences of the offshore area. The data have been interpreted by myself and co-workers in the Marine Geology Research Group of the B.G.S. during preparation of a series of 1:250,000

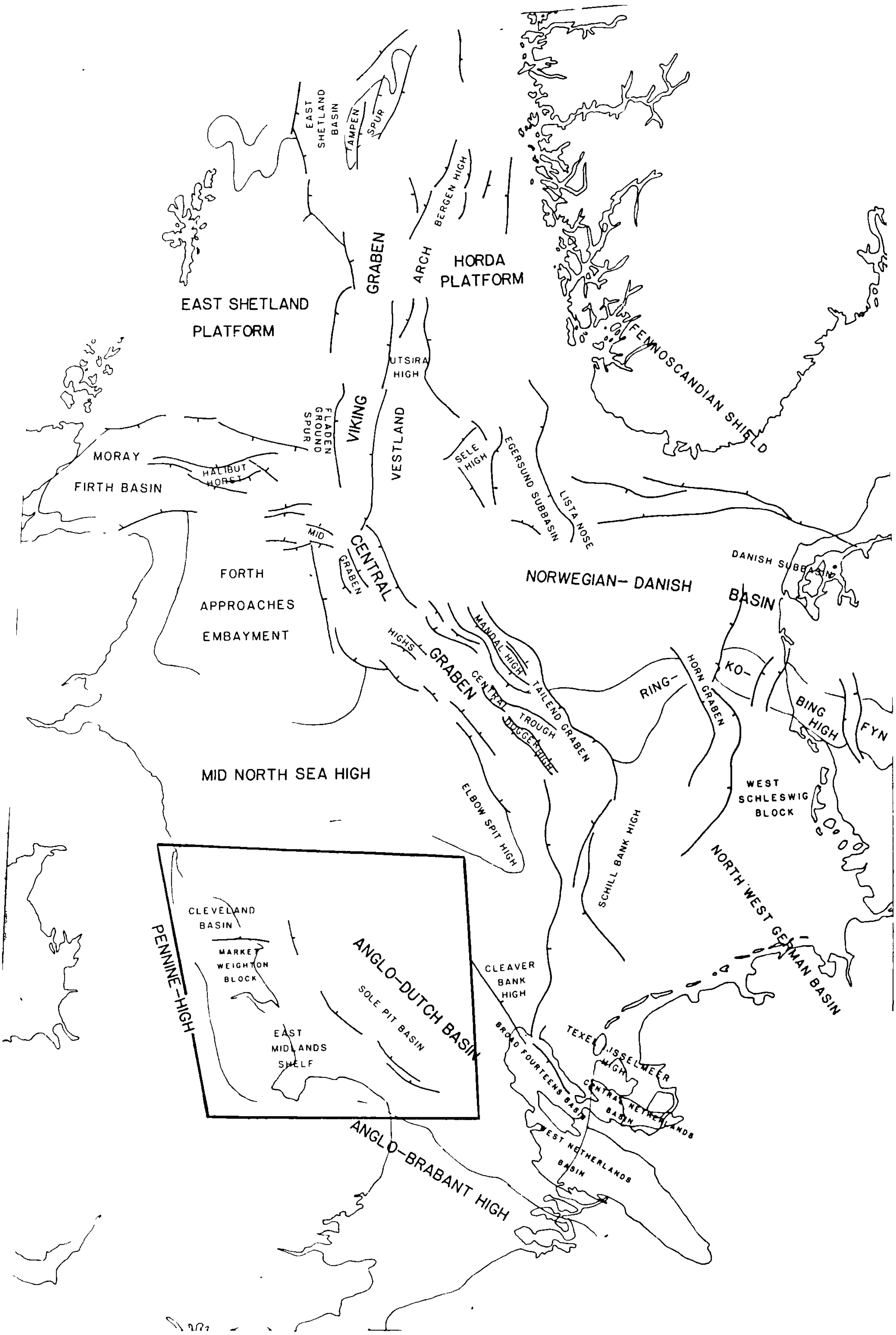


Figure 1.1 Main structural elements of the Southern North Basin and adjacent areas.

scale geological map sheets covering the whole of the Southern North Sea Basin. In the production of the California Sheet (Lott 1985), for example, 4,230km of shallow seismic data were collected and interpreted along a series of E-W and N-S traverses with a grid spacing of about 5km (Chapter 9). The seismic equipment used included **sparker** and **airgun** systems that provided data of exceptional quality, allowing interpretation of the structure and geology of the area to depths of up to 800 metres below seabed. In order to improve the interpretation of this seismic network a series of seabed sampling surveys and shallow drilling programmes were undertaken, between 1979 and 1982, in the southern North Sea area.

Seabed samples of the bedrock were collected using a variety of techniques. In those areas where seismic interpretation and reconnaissance sampling proved a thin Quaternary cover, a gravity core system was widely used to penetrate it. The **gravity corer** is a free-fall sampling device comprising half a ton of lead weights mounted above a 2½ inch diameter sampling tube or barrel. The coring device is released and freefalls from approximately 10 metres above the sea bottom and depending on the lithology encountered, penetrates up to 300mm into the bedrock. In comparatively soft lithologies, as for example the Lower Cretaceous Speeton Clay, a more sophisticated seabed sampler, the **vibrocorer**, was used. Using this device, cores of up to 1.5m long were obtained. In the harder lithologies, as for example the Upper Jurassic Corallian oolitic limestones, a 6 metre seabed **rockdrill** was used. This device is a remotely controlled rotary coring system which can obtain good quality core of 60mm in diameter and up to 6m in length.

Rotary drilling was carried out in those areas where a thick cover of Quaternary sediments masked the bedrock, and also to obtain a few substantial cored sequences. Standard wireline rotary coring techniques were used allowing penetration below seabed of up to 200 metres. In general, however, shorter cored sequences were preferred in order to maximise the number of drilling sites occupied within the basin. Though extremely weather dependent the drilling proved particularly successful with several hundreds of metres of good quality core recovered. The inital results from these drilling projects have been published by the author in 3 publications (Lott et al 1983; Lott 1985; Lott et al 1985; Cox et al in prep.) and a more detailed account is given in this thesis.

The focus of my attention in the southern North Sea has been the California Sheet area (Enclosure 1) largely because much of this area is swept free of sediment, exposing a Jurassic outcrop more extensive than that of the adjacent Cleveland Basin. Further eastwards and southwards the Jurassic and Early Cretaceous successions are buried beneath Upper Cretaceous (up to 1200m) and Tertiary-Quaternary (up to 1800m) sediments (Glennie and Boegner 1981; Lott 1983; Lott 1985).

The present outcrop pattern of pre-Quaternary sediments is presented in Figure 1.3 and derives directly from the B.G.S. surveys of the area. Jurassic and Early Cretaceous strata crop out extensively in the offshore area adjacent to the Cleveland Basin of Yorkshire (beneath a thin , <1 metre, Quaternary cover (Lott 1986)) and along a north-west to south-east trending tract - the Sole Pit Inversion to the south-east. It was largely by concentrating sampling and drilling efforts on these two areas that much of the new data on the stratigraphy of the Jurassic and early Cretaceous successions has been obtained. In the far more extensive areas where a cover of later Mesozoic and Tertiary strata is present the stratigraphy of the Jurassic and Early Cretaceous succession has been determined using released commercial well data.

Despite the penetration of Jurassic sequences in up to 150 commercial

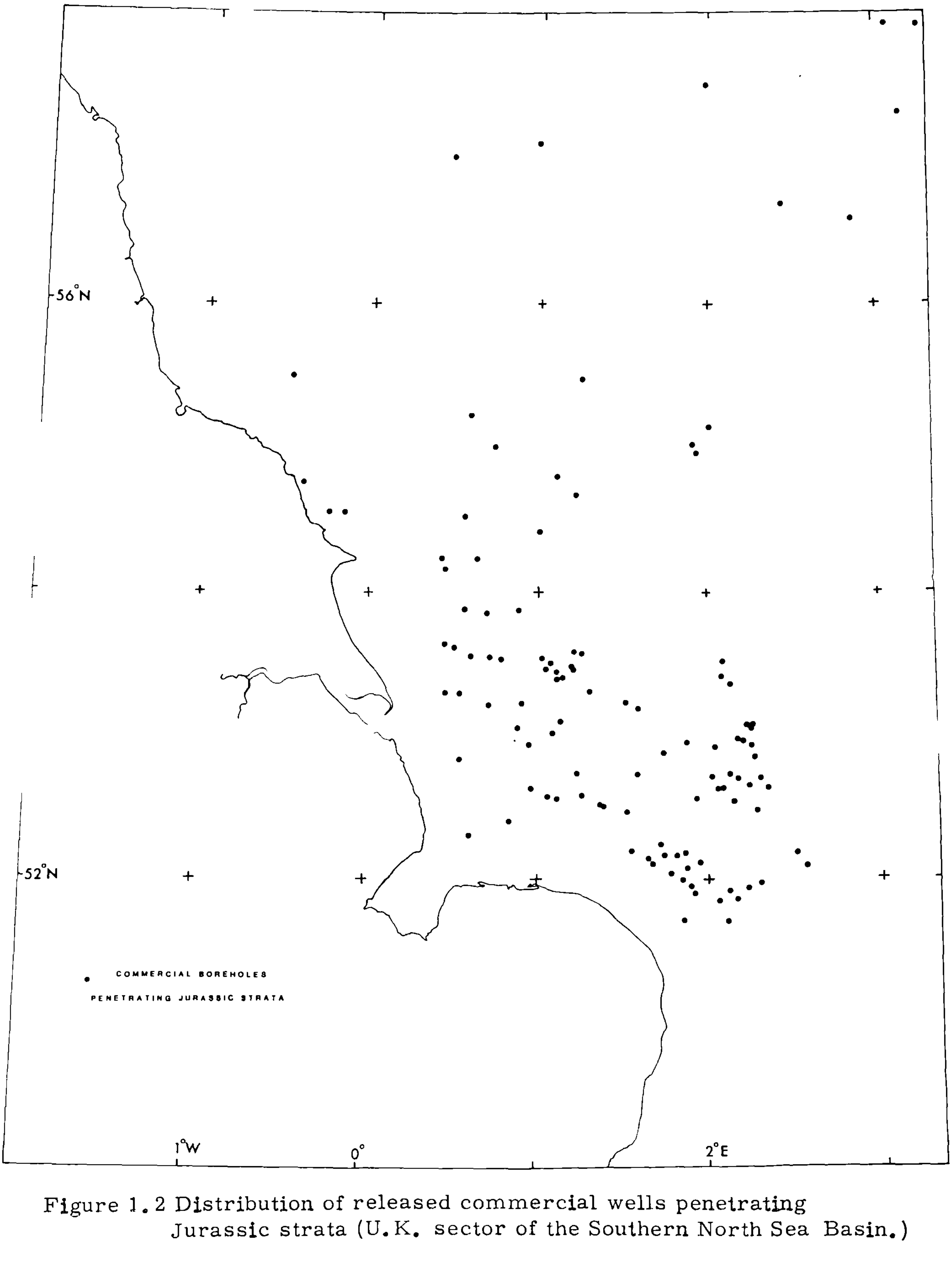


Figure 1.2 Distribution of released commercial wells penetrating Jurassic strata (U.K. sector of the Southern North Sea Basin.)

wells in the Southern North Sea Basin (Figure 1.2), comparatively little lithostratigraphic information has been published, largely because the sediments are non-prospective in terms of hydrocarbon potential. In contrast, the Jurassic clastic sequences north of the Mid North Sea - Rinkobing-Fyn High (Figure 1.1) include some of the largest oil reservoirs in the North Sea oil province e.g. Brent and Fulmar Fields. As a direct consequence of this lack of prospectivity, few commercial cores were taken in the post-Triassic succcession. Practically all the commercial material available from the succession is in the form of rock chips or cuttings. These are chippings of bedrock, generally up to 10mm across, which are flushed from the cutting face of the drill-bit to the rig floor, using a constantly circulating drilling mud system, and subsequently collected by the mud-log analyst from a series of sieve shakers. Calculations using mud pump rate, rate of penetration and depth of hole (information which is constantly monitored by the mud-log analyst) is used to determine the the time taken to flush the rock cuttings from the bit to ground level and hence the depths from which the cuttings originate. The major drawback of the system is the contamination of cuttings by caving from overlying formations as drilling proceeds. In order to establish a more detailed lithological succession, I have re-examined cuttings from a number of wells. In addition I have examined, for comparative purposes, six cored and geophysically logged boreholes from eastern England so that sequences of unweathered cuttings material from offshore are compared with similar fresh material from onshore cores.

The paucity of commercial core material is partly offset by the availability of a comprehensive set of downhole geophysical logs for each borehole drilled. A direct comparison of downhole geophysical log responses with the lithological data derived from cuttings, together with an appreciation of the onshore lithological sequence enables a reasonably accurate reconstruction of the lithostratigraphy of the offshore area. An overall appreciation of the regional lithostratigraphy of the basin is essential when one considers that much of the early drilling (1965-70) and stratigraphic assessments on the composite geological logs were undertaken largely in isolation and comparative secrecy because of company rivalries. In many instances therefore the original released composite logs show a simplified stratigraphy which may now be incorrect. It was not until 1974 with the publication of the I.G.S. / Oil Industry report setting up a lithostratigraphic nomenclature for the Southern North Sea Basin (Rhys 1974) that a more practical and consistent stratigraphy for the basin was established. The lack of hydrocarbon prospects in the post-Triassic successions of the southern North Sea however, ensured fairly scant attention to that part of the sequence, both in the I.G.S. / Oil Industry report and in many subsequent publications. An attempt to redress this imbalance is made in this thesis by re-examining many of the older wells with the specific aim of formulating a more detailed lithostratigraphic subdivision of the Jurassic and to a lesser extent the Early Cretaceous successions.

Many recent studies of large basin areas have emphasised the value of downhole geophysical log correlation in determining basin stratigraphy, particularly in those areas where sample information other than well cuttings is lacking (see for example Lott et al. 1982). In the Southern North Sea Basin most of the wells drilled by commercial companies have a comprehensive suite of downhole geophysical wireline logs. These logs are run using a range of probes which are lowered down the well and which on retrieval record a wide variety of geophysical parameters of the host strata. In the southern North Sea area, although the commercial interests are largely confined to the sandstone gas reservoirs of the Lower Permian (Rotliegendes) and Triassic (Bunter Sandstone) sequences, geophysical logs are also available for the overlying Jurassic to Quaternary successions. From these suites of logs the **Borehole Compensated Sonic Log (B.H.C.S.)** and **Gamma Ray Log (G.R.)** are widely available and have proved particularly useful in correlating the Jurassic sequences across the Basin.

The BHCS Log effectively measures the travel time, from source to recorder, of acoustic signals transmitted from the downhole probe. The travel time determined in this way varies as the density of the rock type, itself a function of lithology, changes. For example the velocity of an acoustic signal transmitted through a hard, dense oolitic limestone such as the Lincolnshire Limestone (Middle Jurassic) or Corallian Limestone (Upper Jurassic) shows a correspondingly short travel time when compared with the velocity of the same signal through poorly consolidated porous sandstones and soft clays, as for example in the Middle Jurassic, Upper Estuarine Series. Using this tool therefore the downhole log response may be used to determine the broad rock sequence in terms of well or poorly cemented sediments. Laboratory determined measurements of, for example, the velocities of acoustic signals through limestones (20,000 ft/sec), unconsolidated sandstone (17,000 ft/sec), halite (15,000 ft/sec) and anhydrite (20,000 ft/sec) (Schlumberger 1972) give some idea of the variation encountered in different rock types and show the potential of the BHCS tool as an aid to determining rock lithology.

In order, however, to improve on this very basic lithological determination the BHCS log is often widely used in conjunction with the Gamma Ray Log. The GR response is a measure of the naturally occurring radioactivity of different rock types encountered downhole. In effect the GR tool measures the total potassium-thorium-radium-uranium content of the host strata by measuring the naturally emitted gamma-rays from these elements. The abundance of these elements varies according to rock-type, they are characteristically high in clay-rich sediments and less significant in for example limestones or quartzose sandstones. The organic-rich Kimmeridge Clays, for example, show a high gamma ray response - including the so-called 'hot-shales' - while quartzose sands, limestones or halites show low responses. When the GR and BHCS logs are interpreted together it is possible to make a reasonably accurate assessment of lithology, particularly when used in conjunction with rock cuttings over the interval. There are, however, pitfalls. An abundance of potash-felspar, mica, or an anomalously high heavy mineral concentration e.g. zircon may produce enhanced GR responses in a sandstone. Similarly some sandstones may have an unusual cementation e.g. Rhaetian sandstones within the California sheet area often have an gypsum/anhydrite cement which significantly increases the velocity profile on the BHCS log.

Correlations using the GR and BHCS are, as has been noted, often used for assessments of the lithostratigraphy of a basin (see for example Deegan and Scull 1977). If, to take the whole process one stage further, a cored borehole sequence is available with a comprehensive suite of downhole logs , the comparison of log response to a particular lithology can be considerably enhanced. In Figure 4.4 the log responses (GR and BHCS) are displayed for the Jurassic succession of selected boreholes in the Southern North Sea Basin and, by comparing these log response profiles with logged and cored Jurassic successions from the East Midlands and south Yorkshire areas the continuity of many of the lithological units into the offshore area may be demonstrated.

1.3. Previous work

1.3.1. History of research.

Our present knowledge of the geology of eastern England is essentially a synthesis of more than 150 years of geological research by many scores of workers; in contrast our knowledge of the geology of the offshore area of the Southern North Sea Basin has been aquired over a comparatively short period. Interest in the geology of the area has been sporadic and prior to 1960 largely limited to academic studies (Collette 1958). However the discovery of a major gas reservoir in the Early Permian (Rotliegendes) sandstones of the Groningen province (Netherlands) encouraged commercial interest in the offshore area and gave considerable impetus to further studies of the geology of the Basin. Early geological assessments of the basin were initially based upon gravity and magnetic survey data and were interpreted by direct comparison with the well-established geological successions of the adjacent West Netherlands and North West German onshore basins. By 1962 several commercial seismic surveys were under way and the establishment of internationally agreed national boundaries within the North Sea basin in 1964 promoted further interest in these offshore areas (Cook 1965).

Academic research in the U. K. sector of the basin at this time was largely limited to the work of Donovan and his co-workers at Hull University (Donovan 1963, 1968; Donovan and Dingle 1965), who carried out a number of geological and geophysical traverses within the basin and who also completed the first extensive geological survey of part of the basin (1964-66) off the coast of north-east England (Dingle 1971).

Geological information from the offshore area was therefore limited until the publication of preliminary results from early commercial deep drilling in the Basin (Kent 1967). A considerable range of publications have appeared since that time notably those of Rhys (1974), Kent (1975, 1980b), Woodland (1975), Selley (1977), Illing and Hobson (1981) and

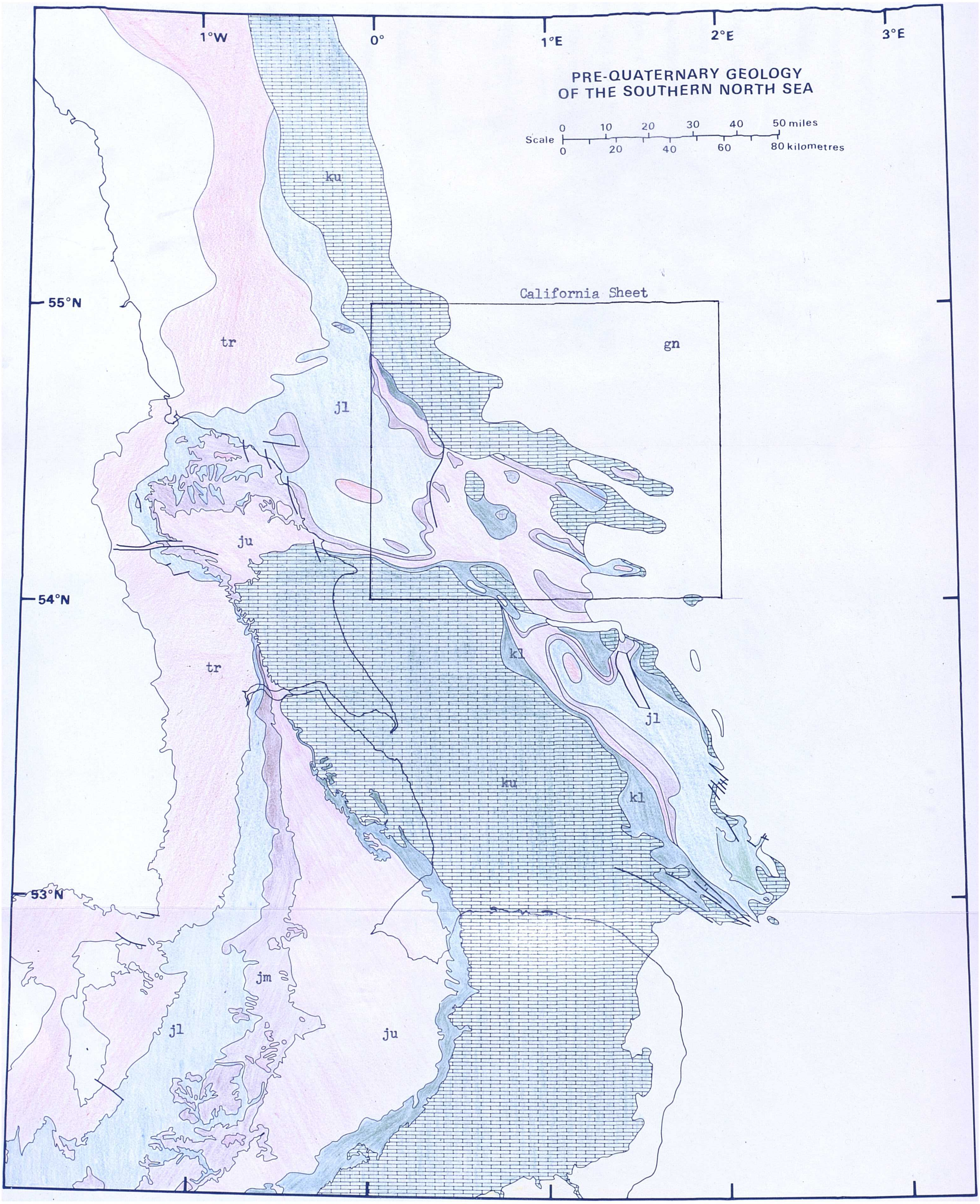


Figure 1.3 Pre-Quaternary geology of the southern North Sea.
gn-Tertiary, ku-Upper Cretaceous, kl-Lower Cretaceous,
ju-Upper Jurassic, jm-Middle Jurassic, jl-Lower Jurassic,
tr. -Triassic. -Permian

Ziegler (1982). Much of the emphasis in these publications is naturally focused on details of the stratigraphy, petrography and petrology of the gas reservoirs, with only broad assessments of the non-prospective post-Triassic sequences. The most recent regional geological studies of the basin have stemmed from the systematic survey of the U.K. Shelf by the British Geological Survey (BGS). The information collected is being published as a series of 1:250000 Solid Geological map sheets covering the whole of the U.K. Continental Shelf (e.g. Lott 1985). The Survey began work in the Southern North Sea Basin in 1979 and shipboard operations were largely completed by 1984. The final map series is being produced from the interpretation of many thousands of kilometres of shallow seismic data integrated with seabed sample data and including shallow cored borehole sequences. The maps also include data from the many commercial wells released from confidentiality by the Department of Energy, on behalf of the oil companies, from 1975 onwards.

1.4. A structural outline of the southern North Sea during the Late Triassic to Early Cretaceous.

The southern North Sea may be divided into a series of major structural elements each of which had important effects on sedimentation in the basin during the Mesozoic. These structural elements, which are first apparent during the Early Permian (Rotliegendes) phase of sedimentation can be broadly divided into those areas that remained, throughout much of its early history, as positive, stable blocks supplying sediment to the basin and those areas which subsided differentially to receive considerable thicknesses of sediment (Figure 1.1).

1.4.1. East Midlands Shelf

This shelf area extends eastwards from the Pennine High to the Sole Pit

Trough, and is separated from the latter by the Dowsing Fault Zone, a zone of complex en echelon faulting along which several phases of movement can be distinguished (Glennie and Boegner 1981). The shelf is a shallow basinal area, at present buried beneath a Cretaceous Chalk cover, over which subsidence was slow, during the Rhaetian and Jurassic, when compared with the expanded successions in the adjacent troughs. The Jurassic sequences over this shelf are stratigraphically the most complete in the Southern North Sea Basin and reach a maximum thickness of c 650m (47/18-1, Ulceby Cross borehole) in the southern part of the shelf area. They thin further southwards against the Anglo-Brabant High and also thin northwards onto the Market Weighton High. During the Early Cretaceous this comparative stability of the East Midlands Shelf was maintained with the deposition of thin (maximum of 170m, 48/17-1) littoral and shallow marine sand and clay successions.

1.4.2. Anglo-Brabant High

This extensive positive area stretching from Belgium to East Anglia formed the southern boundary of the Southern North Sea Basin until the Early Cretaceous. Many of the post-Carboniferous successions within the basin thin and overstep southwards onto the high (Kent 1947; Donovan et al 1979). Links with the southern England area were maintained intermittently around the western margin of the high (Anderton et al.1979), but it was not until Albian times that final submergence of the high appears to have taken place.

Recent interpretations of gravity data from the area suggest that the stability of the high may be related to the buoyancy effects of granite intrusions at depth, a factor also considered to be important in maintaining the stability of the Market Weighton and the Mid-North Sea Highs (Bott et al 1978; Donato and Tully 1981; Chroston and Sola 1982).

1.4.3. Market Weighton High

This High is best defined by the thin Jurassic sequences (<50m in Hornsea and North Dalton boreholes) along the northern margin of the East Midlands Shelf. The stability of the high has been attributed to the presence of granitic masses at depth. Recent interpretations suggest the high is a southward tilted structure, fault bounded on its northern margin (the east-west trending Coxwold-Gilling fault zone). Rhaetian sediments extend over the block, but the Jurassic sequences thin and overlap northwards onto its southern margin (Kent 1980b). Along the western margins of the block the Jurassic sequences at outcrop show some thickening, whilst eastwards in the offshore area a north-north-west trend to the structure is suggested by isopach data from released commercial wells (Figure 3.1). Early Cretaceous sediments are either thin (e.g. Carstone) or absent over much of the high but thicken to the east and north.

1.4.4. Cleveland Basin

This basin occupied a rapidly subsiding east-west trough to the north of the Market Weighton High (Figure 1.1). The present broad anticlinal structure of the area is a result of gradual inversion possibly commencing as early as the Bathonian, but essentially taking place in Cretaceous and mid-Tertiary times. Sediment thicknesses increase towards the faulted southern margin of the trough and reach a maximum thickness of c.700m (Wykeham borehole). Most of the present basin area lies within the confines of the land area with its offshore extent delimited by the west-north-west trending Scarborough Dome (Figure 6.1). It appears likely from lithological evidence that the Cleveland Basin was, at least during the Jurassic, contiguous with the Sole Pit Trough.

1.4.5. Sole Pit Trough

The Sole Pit Trough, like the Cleveland Basin, formed an area which during the Jurassic subsided more readily than the adjacent East Midlands Shelf to the west. This trough was first established in the Early Permian and underwent inversion from mid-Cretaceous times onwards so that at present the site of this major Jurassic depocentre is a broad arch of folded Triassic and Jurassic strata lying beneath a thin Quaternary cover. The isolated remnants of Jurassic sediments that remain, occupy a series of north-north-west trending synclinal structures, while along the Dowsing Fault Zone at its western margin, extreme thickening of the Jurassic sequence (950m+ in well 48/6-5) is apparent. The structure of the Sole Pit area is further complicated by the development, since Middle Triassic times of major Zechstein salt diapirs and salt withdrawal features which cause syndepositional thickening and thinning of the Jurassic sequence.

1.4.6. California 'pillow and trough' area

The area to the east of the Scarborough Dome and lying along the southern margin of the Mid-North Sea High, is characterised by an extensive area of north-west trending anticlinal and synclinal structures generated by spasmodic halotectonic movement from Middle Triassic times onwards. The Late Triassic and Jurassic successions thin northwards onto the Mid-North Sea High, but links via the Central Graben with the Northern North Sea Basin seem likely particularly during the Upper Jurassic. Early Cretaceous sediments thin northwards onto the high and by Albian times the greater part of the high was submerged.

1.4.7. Anglo - Dutch Basin.

This basin, lying to the east of the Sole Pit Trough, separates the remnant Jurassic sequences of the U.K. sector of the Southern North Sea Basin from the Jurassic succession of the West Netherlands Basin. Connections undoubtedly existed across the area during the Jurassic and Early Cretaceous, but much of the sequence has been removed during post-Jurassic inversion of the area. Since Upper Cretaceous times the area has undergone renewed subsidence so that a thick sequence of Late Cretaceous, Tertiary and Quaternary sediments occupy the basin.

CHAPTER 2

The stratigraphy of the Late Triassic (Rhaetian) Winterton Formation in the Southern North Sea Basin.

The stratigraphy of the Late Triassic (Rhaetian) Winterton Formation in the Southern North Sea Basin.

2.1. Introduction

The topmost part of the Triassic succession in eastern England comprises a sequence of interbedded marine and brackish-water shales and thin sandstones known as the Penarth Group (Warrington et al. 1980). These sediments mark the transition from the arid red-bed sequences, which dominate much of the Permo-Triassic of North West Europe, to the shallow marine environments of the Jurassic. The precise base of the Jurassic is defined, using palaeontological criteria, at the first appearance of ammonites in the succession and therefore the lowest few metres of non-ammonite bearing marine shales are included in the Triassic system (Cope et al. 1980). The lack of cored material from the offshore part of the Southern North Sea Basin, however, does not allow such a precise positioning of the base of the Jurassic and the boundary has therefore been placed at a rather loosely defined lithological transition at the top of the Triassic succession (Rhys 1974). These transitional beds are termed the **Winterton Formation** and were broadly equated with the Rhaetian strata of onshore eastern England (Rhys op. cit.).

A reappraisal of these transitional beds suggests that the sequence may be usefully divided, on the basis of log response, into two distinct units which are widely traceable throughout the U.K. sector of the basin and

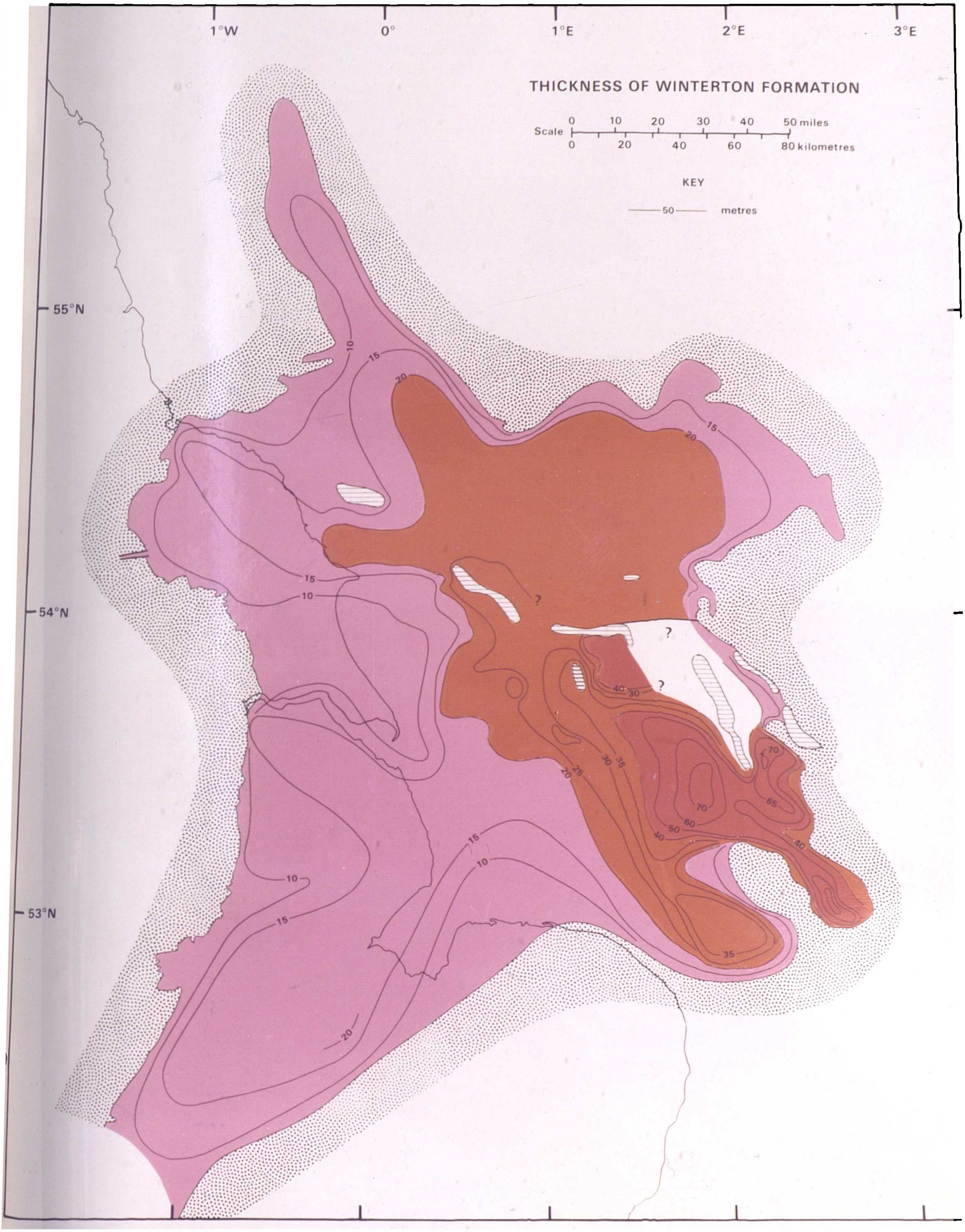


Figure 2.1 Thickness (metres) of Late Triassic (Winterton Fm.) sediments in the Southern North Sea Basin.

which show a gradual eastward thickening into the area of the Sole Pit Trough, and considerable local thickening in the rim synclines of the major salt diapirs within the basin (Figure 2.1).

2.2. Rhaetian stratigraphy

2.2.1. Eastern England - Penarth Group (Warrington et al 1980).

The Penarth Group is divided over much of the area into two formations, an upper sequence of green-grey and brown mudstones forming the Lilstock Formation, and a lower sequence of dark grey shales with sandstones forming the Westbury Formation. These beds rest on greenish-grey marls of the **Blue** Anchor Formation, a sequence which exhibits the first signs of an amelioration of the environment prior to the main Rhaetian transgression into the basin.

East Midlands (Kent 1953; Gaunt et al.1979).

Lower Rhaetic Beds (Westbury Formation)

The **Westbury Formation** comprises a sequence of dark grey to black fissile shales. Fossil debris is common, together with occasional thin, cross-bedded sandstone beds. In wells from the East Midlands area the formation typically shows a high gamma response, in marked contrast to the underlying low gamma response from the marls of the Blue Anchor Formation.

Upper Rhaetic Beds (Lilstock Formation).

The **Lilstock Formation** comprises pale grey and greenish-grey and brown, silty shales, with occasional sandstone beds.The formation shows a more moderate, uniform gamma response than the underlying black shales of the Westbury Formation.

Cleveland Basin (Raymond 1955).

Strata of the Penarth Group are only known from borehole sections in the Cleveland Basin. The Westbury Formation, which comprises interbedded black shales and pale grey sandstones rests on pale grey, dolomitic mudstones of the Blue Anchor Formation. The shales are rich in carbonaceous material and are often bituminous. Pyritised fossil debris is common. The thin sandstone beds consist of fine to medium grained quartz, are micaceous and slightly calcareous.

The overlying sediments of the Lilstock Formation comprise soft, pale grey to brown mudstones, with a thin basal, silty and sandy micaceous shale.

2.2.2. Southern North Sea Basin - Winterton Formation.

The beds transitional between the Triassic and Jurassic successions of the offshore area have been penetrated in a large number of wells within the U. K. sector. However, the only cored material available from the Winterton Formation was obtained in BGS shallow cored borehole 81/44 (Figure 2.2), which was drilled on the flanks of the Scarborough Dome c.19km east of Filey Bay on the Yorkshire coast (54^{o}20.323'N 0^{o}00.950'W). The site was chosen because an examination of shallow seismic profiles and seabed samples had suggested that Triassic red mudstones were at outcrop at seabed along the axis of the structure surrounded by dark grey mudstones of Jurassic (Hettangian) age (Enclosure 1, Figure 1.3). Drilling commenced in a thin Quaternary sequence passing abruptly into greenish-grey, dolomitic mudstones, overlying c.7m of dark grey to black fissile mudstones which in turn rest abruptly on hard pale greenish-grey dolomitic mudstones. The drilling was terminated at 17.10m in dolomitic mudstones. A detailed examination of the cores suggests the following stratigraphy for the sequence.

0 - 3.25m Quaternary

3.25 - 6.26m No recovery

6.26 - 6.46m. This interval consists of hard greenish-grey mudstones, which are dolomitic with a blocky fracture. The mudstones lack macrofossils.

Palynological preparations from this unit yielded only poor assemblages, but dinoflagellate cysts and other organic-walled microplankton were present suggesting marine influences *in* the sequence (*Dr G. Warrington* pers. comm. 1983). The lithology suggests that this interval is probably part of the Lilstock Formation of the Penarth Group.

6.46 - c.13.5m. This interval consists predominantly of dark grey to black, pyritic, bituminous mudstones and siltstones, interbedded with paler sandstone units. Pyritised fossil debris is very common forming thin shell 'plasters' on some bedding planes. The mudstones are fissile with a smooth fracture and often have thin bituminous bands. The paler sandstone lenses and bands show a range of sedimentary structures including low-angle cross-bedding, convoluted, crenulate and flaser bedding. Bioturbation is very common with subvertical <u>Teichichnus</u> burrows and tube-like branching burrows on some bedding planes. The sandstones are subarkosic packstones, with grainstone patches. They are very fine to fine grained, often micaceous with pyritic patches and may form units up to 0.30m thick. The sandstones become more prominent towards the base of the interval. A number of thin sections from the sandstones were examined and the results are presented in Table 2.1. Some of the sandstones show a distinctive poikilotopic gypsum cement.

TABLE 2.1

Thin section point count data from the Late Triassic sandstones in borehole 81/44 (200 grains) %

Depth (Metres)	QM	QP	KF	G	C	M	P	A	M
8.44	66	1	13		1	14		5	
8.88	60	1	11	4	6	5		13	
12.80	68	1	5	23	1	1	1		
13.80	57	3	5	33	P	P			

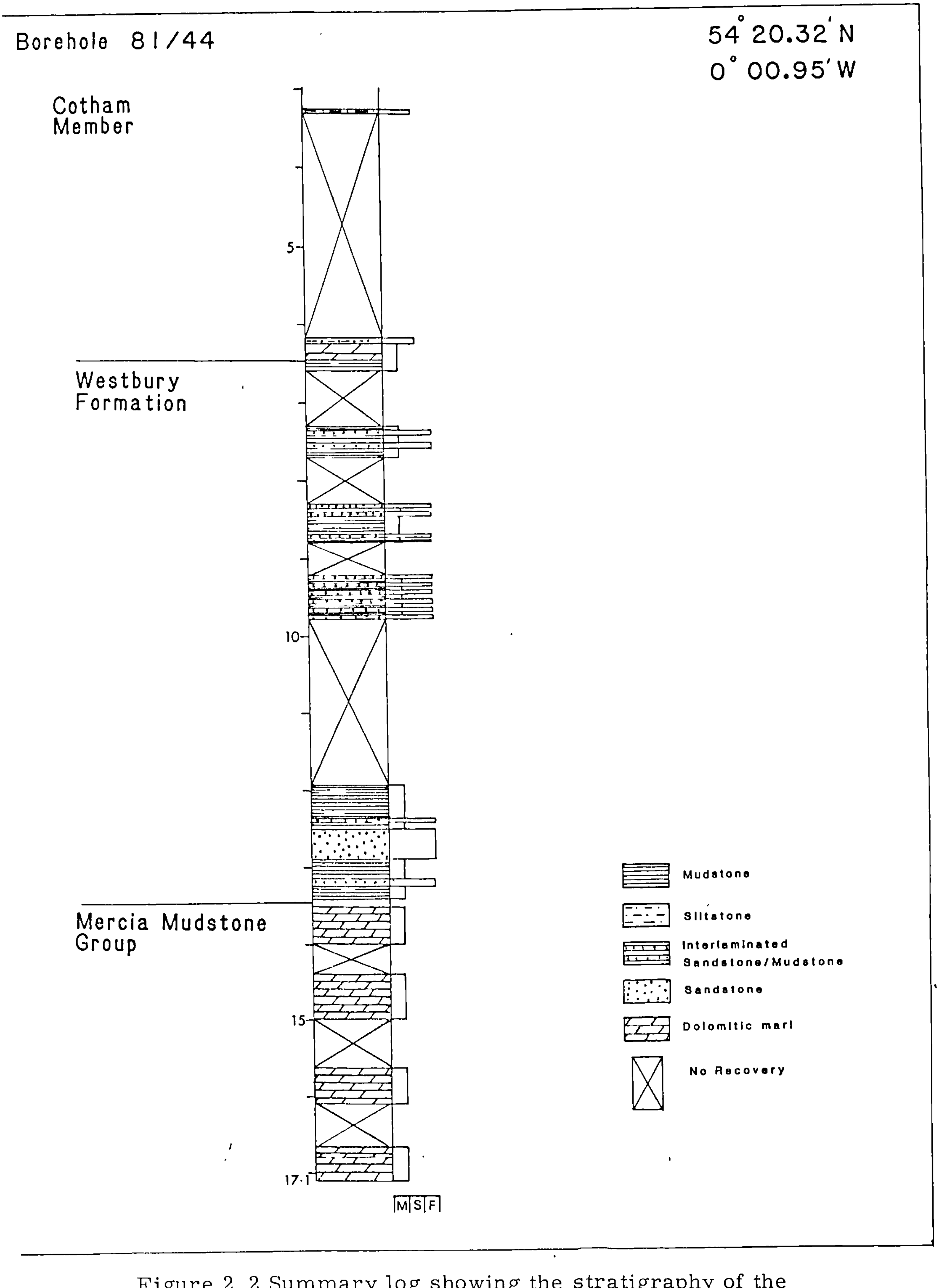


Figure 2.2 Summary log showing the stratigraphy of the Rhaetian succession cored in borehole 81/44.

QM - quartz (monocrystalline), QP - quartz (polycrystalline), KF - potash feldspar, G - gypsum cement, C - carbonate cement, M - mica, P - pyrite, A - anhydrite, M - clay matrix.

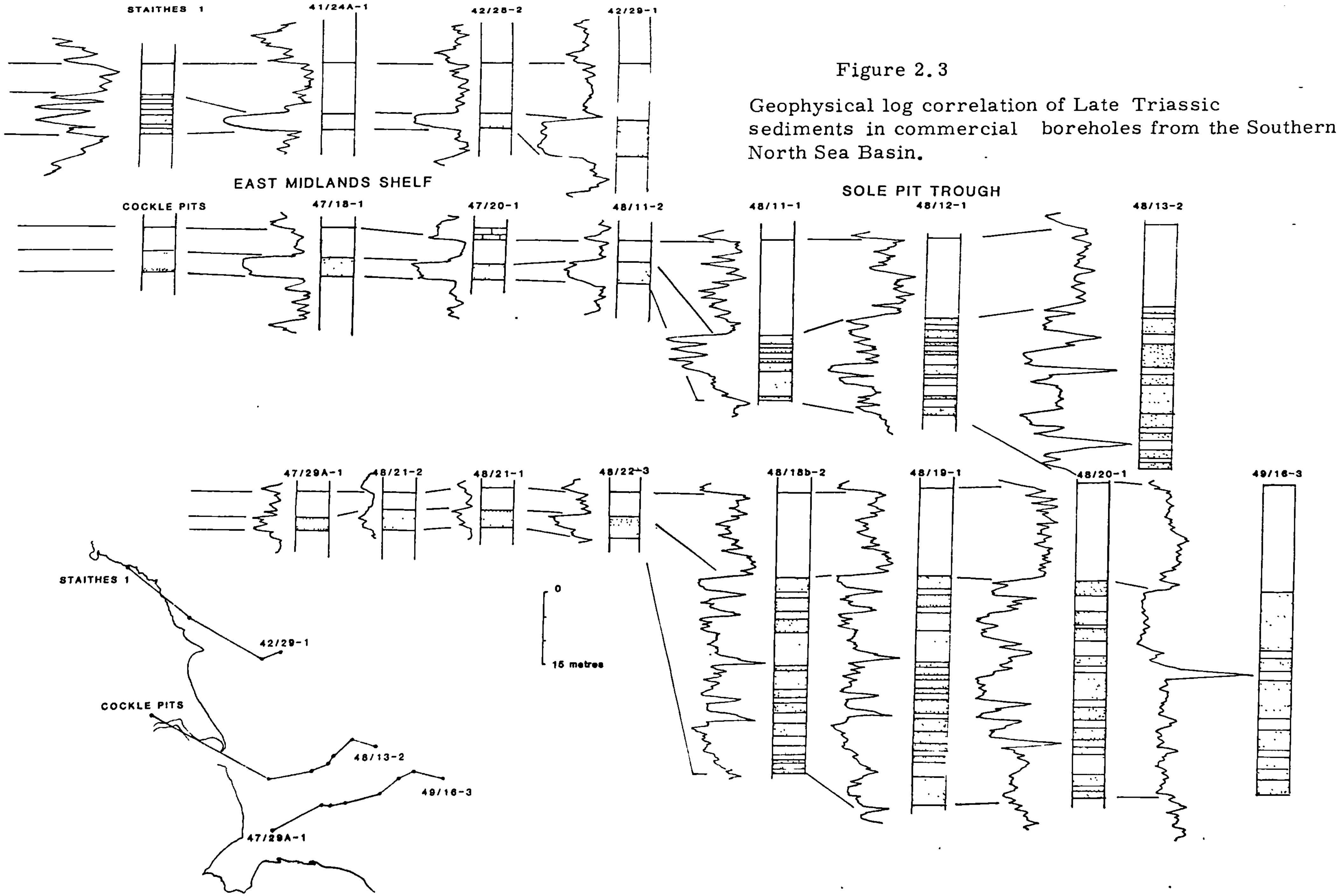
These dark organic-rich mudstones yielded good assemblages of bivalves and some fish debris. Dr Ivimey-Cook (pers. comm. 1984) comments that the fauna is characteristic of the Westbury Formation and includes the taxa Eotrapezium concentricum (Moore), "Modiolus" sodburiensis Vaughan, Rhaetavicula contorta (Portlock) with fish remains including Gyrolepis alberti Agassiz . Palynological preparations from these mudstones were also diagnostic of a Rhaetian age for the sequence. The miospore associations included Ricciisporites tuberculatus Lundblad 1954, Ovalipolis pseudoalatus (Thiergart) Schuurman 1976 and Rhaetipolis germanicus Schultz 1967. Organic-walled microplankton, including Rhaetogonyaulax rhaetica (Sarjeant) Loeblich & Loeblich emend. Harland et al. 1975 were also present (Dr G. Warrington pers. comm. 1983). Further details of the palaeontology of the borehole are available from the unit files of the Marine Geology Research Group of the B.G.S. (Keyworth).

13.5 - 17.10m. T.D. The beds of this interval consist of pale greenish-grey, hard, dolomitic mudstones. They show a blocky or sub-conchoidal fracture and were non-fossiliferous. Their position beneath the black shales and sandstones of the Westbury Formation strongly suggests they form part of the 'Tea Green Marls' of the Blue Anchor Formation (Triton Anhydritic Formation of Rhys (1974)).

In the commercial wells close to borehole 81/44 (e.g. 41/24A-1,

Figure 2.3

Geophysical log correlation of Late Triassic sediments in commercial boreholes from the Southern North Sea Basin.



41/25A-2) the Winterton Formation is closely comparable in thickness. The log responses for the interval, particularly the G.R. and B.H.C.S, allow further correlation between the cored sequence and the uncored wells further into the basin (Figure 2.3).

The top of the Winterton Formation is marked by a decrease in G.R. response and increase in B.H.C.S. response representing the widespread basal limestone unit of the Jurassic, equivalent to the 'Hydraulic Limestone' (Kent 1980b). On the basis of the log responses the formation may be divided into two units: an upper unit of mudstones with a comparatively high gamma response, and a lower interval of mudstones, interbedded with thin, pale grey sandstones at the western margin of the basin, but increasingly dominated by sandstones in the thicker successions to the east. The sandstones of this lower unit show a low gamma response, with comparatively high gamma peaks from the interbedded shales.

The upper unit reaches its maximum development (c.30m) in the southern part of quadrants 48 and 49 (Figure 2.3) e.g. wells 48/30-3x, 49/16-3, 49/17-3. The thickening of the Rhaetian sequence in these wells appears to be largely related to the strongly developed salt diapirs in this part of the basin and a similar thickening is seen in the Lower Jurassic successions in the area. The unit shows a comparatively high, uniform gamma response and can be traced over most of the basin (Figure 2.3).

The lower subdivision of Winterton Formation is more variable in thickness. It comprises a series of very fine, silty sandstones interbedded with thin shales and reaches a maximum thickness c.44m in well 49/21-2. This well was defined as the type well for the Winterton Formation by Rhys (1974) and this lower interval was termed the Rhaetic Sandstone Member. Few of the surrounding wells show such a consistent sand development as that of the type section. In most wells the Gamma profile is more ragged suggesting a greater proportion of shaly interbeds in the sequence (Figure 2.3). In the type section, the base of the Winterton Formation was placed within a thin mudstone interval, with an overall high gamma response, at the top of the **Triton Anhydrite Formation.** There appears to be no valid reason for placing the boundary within this unit and it would seem to be of more practical use to place the formation boundary beneath the lowermost sandstone unit.

2.3. Comparison with adjacent basins.

2.3.1. West Netherlands Basin (RGD / NAM 1980).

The Late Triassic succession of the West Netherlands Basin is known as the **Sleen Shale Member.** The top of the sequence, as in the UK sector is defined by the overlying development of a thin but persistent argillaceous limestone unit at the base of the Jurassic. The Sleen Shale Member consists predominantly of grey and brown marine shales, but a thin sandstone interval is locally developed.

2.3.2. Norwegian - Danish Basin (Bertelsen 1978).

The Late Triassic succession of the Norwegian - Danish Basin comprises the Vinding and Gassum formations. The **Vinding Formation** comprises claystonesand limestones of Late Norian to Rhaetian age, equivalent in part therefore to the Blue Anchor Formation of the onshore U.K. and representing the first effects of the Late Triassic climatic amelioration in the area. This unit is overlain by the **Gassum Formation,** of Rhaetian to Hettangian age, which is a sequence of interbedded sandstones and claystones. Locally the unit may be finely laminated, carbonaceous and pyritic. Occasional coaly horizons occur. The sequence has been interpreted as a fluvio-deltaic deposit (Larsen 1966). A tripartite division of the sequence into a lower interval of coarsening-upward sandstone units of fluvio - deltaic origin, a middle interval, which is more clayey and characterised by a restricted fauna including the bivalve Rhaetavicula contorta (Portlock) deposited in an anaerobic environment, and an upper interval of paler grey and brown claystones and sandstones deposited in a lagoonal setting. The thick, basal sandy developments of the Late Triassic sequence in the Danish Basin, probably sourced from the Rinkobing-Fyn High, suggest a possible model for the sands developed in the eastern part of the U.K. sector of the North Sea Basin. It is possible that they represent deposition in a similar environment adjacent to the Mid-North Sea and Cleaver Bank Highs. The GR responses for these sandy intervals in the U.K. sector certainly suggest a series of stacked, coarsening-upward sand units (Figure 2.3).

The overlying middle interval, in the Danish Basin, with its restricted marine fauna and dark carbonaceous clays, suggests a similar depositional environment to the Westbury Formation (Penarth Group) and represents the initial transgression of the sea into the area. Subsequently a reversion to lagoonal deposition, shown in the sediments of the uppermost unit, mirror the change that occurs in the U.K. in the latest Triassic sediments of the Lilstock Formation.

2.4. Conclusions

The division of the Winterton Formation into two mappable units may be demonstrated in virtually all those wells which have penetrated Rhaetian strata in the U.K. sector of the North Sea. It is, however, given the lack of cored material from the area, more difficult to precisely tie the two units recognised into the present lithostratigraphic nomenclature of Warrington et al.(1980) for the Penarth Group. When core material is available, as in B.G.S. borehole 81/44, the offshore succession can be convincingly correlated with the onshore sequence and the current nomenclature applied (see above). The considerable thickening of the

Winterton Formation in the offshore area, however, precludes a precise correlation with the Penarth Group, but it appears reasonable to assume that the upper mudstone unit is a likely correlative of the Lilstock Formation, while the lower interval with its eastward thickening sand units and shaly interbeds may equate with the Westbury Formation. The thick sandstone units developed in the eastern part of the basin may have a similar origin to the Late Triassic sandstones of the Norwegian - Danish Basin, as localised fluvio - deltaic sequences developed adjacent to the Cleaver Bank High.

CHAPTER 3

The distribution and thickness of Jurassic strata in the U.K. sector of the Southern North Sea Basin.

The distribution and thickness of Jurassic strata in the U.K. sector of the Southern North Sea Basin.

3.1. Introduction

During the Jurassic the U. K. sector of the southern North Sea formed part of a Jurassic basin which extended eastwards from eastern Britain into Germany and the Netherlands; northwards, via the Central Graben into the Norwegian-Danish Basin and southwards into the Anglo-Paris Basin (Zeigler 1984). Such an extensive basin of deposition necessarily encompassed a wide range of depositional environments, which are reflected in the considerable facies variations over the basin particularly during the Middle and Upper Jurassic. Subsequent tectonism and erosion, primarily during the Late Jurassic - Early Cretaceous divided this basinal area into a series of isolated basin remnants, which in the North Sea area are now largely preserved beneath extensive Cretaceous, Tertiary or Quaternary sequences.

The classic British Jurassic successions of Eastern England at present therefore, form only the western margin of one such Jurassic basin remnant, the Southern North Sea Basin, by far the greatest proportion of which lies offshore beneath the southern North Sea. This basin remnant conveniently lies wholly within the U.K. sector of the Basin.

The series of maps presented in this paper (Figures 3.1 - 3.6) are intended to define the limits of this Jurassic basin remnant and to illustrate the broad relationship of the intensively studied onshore succession to the comparatively poorly known offshore sequence. The maps presented are primarily derived from a study of the extensive collection of oil company deep borehole data, released from confidentiality by the Department of Energy since 1975. In order to improve the accuracy of the maps, particularly in those areas where Jurassic strata outcrop at seabed,

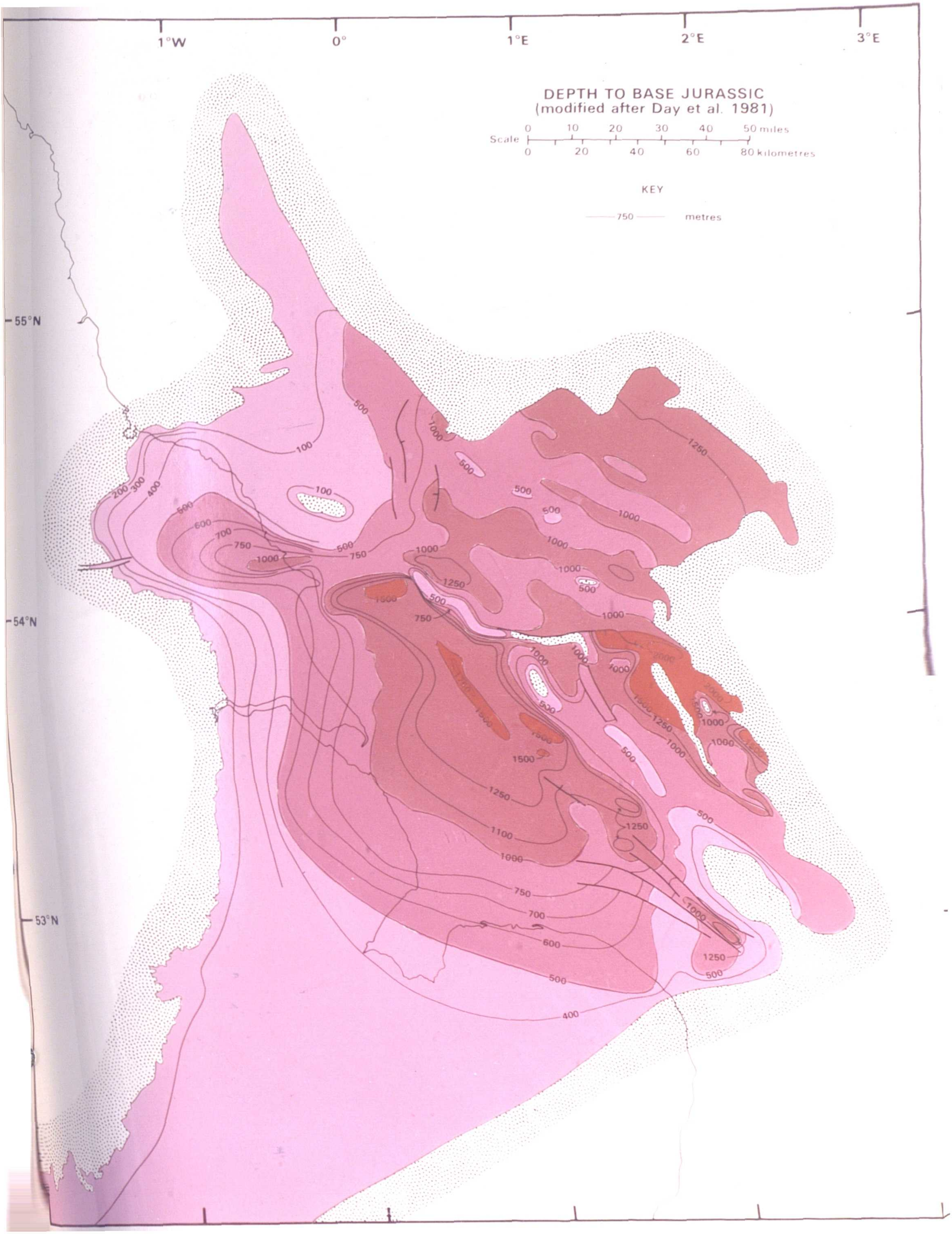


Figure 3.1 Structure contour map on the base of the Jurassic.

geological and geophysical data from recent surveys conducted by the British Geological Survey over the basin were incorporated. ' Despite the drilling of over 150 commercial wells through the Jurassic succession of the southern North Sea Basin (Figure 1.2), comparatively little has been published of the detailed stratigraphy of the sequence. The poor prospectivity of the Jurassic, in terms of hydrocarbon potential, south of the Mid-North Sea - Rinkobing-Fyn High (Figure 1.1), has meant that few cores were cut in the sequence. In 1974 the publication of a joint I.G.S. / Oil industry report (Rhys 1974), setting up a preliminary lithostratigraphic nomenclature for the Southern North Sea Basin, established a more practical and consistent stratigraphy for the Basin but was limited in its coverage of the Jurassic succession, partly as a consequence of its lack of prospectivity, but also because of constraints on the availability of certain wells at that time. A number of subsequent publications, notably Kent (1975, 1982), Woodland (1975), Selley (1977), Glennie and Boegner (1981) and Brown (1984), have presented further summaries of the Jurassic succession of the Basin.

3.2. Distribution

The Jurassic succession of the southern North Sea is most completely preserved beneath a thick cover of Cretaceous strata over the East Midlands Shelf (Figure 1.1). Over this Shelf area the Cretaceous cover reaches 1000m in thickness and the lithostratigraphy of the Jurassic sequence is known only from deep borehole data. A correlation of downhole geophysical logs from these boreholes with cored and geophysically logged sequences in Lincolnshire (Nettleton Bottom Borehole) and South Yorkshire (Brown Moor borehole) (Figures 3.8, 3.9) suggests that the Jurassic sequences of these onshore and offshore areas compare quite closely in lithology (Figure 4.1).

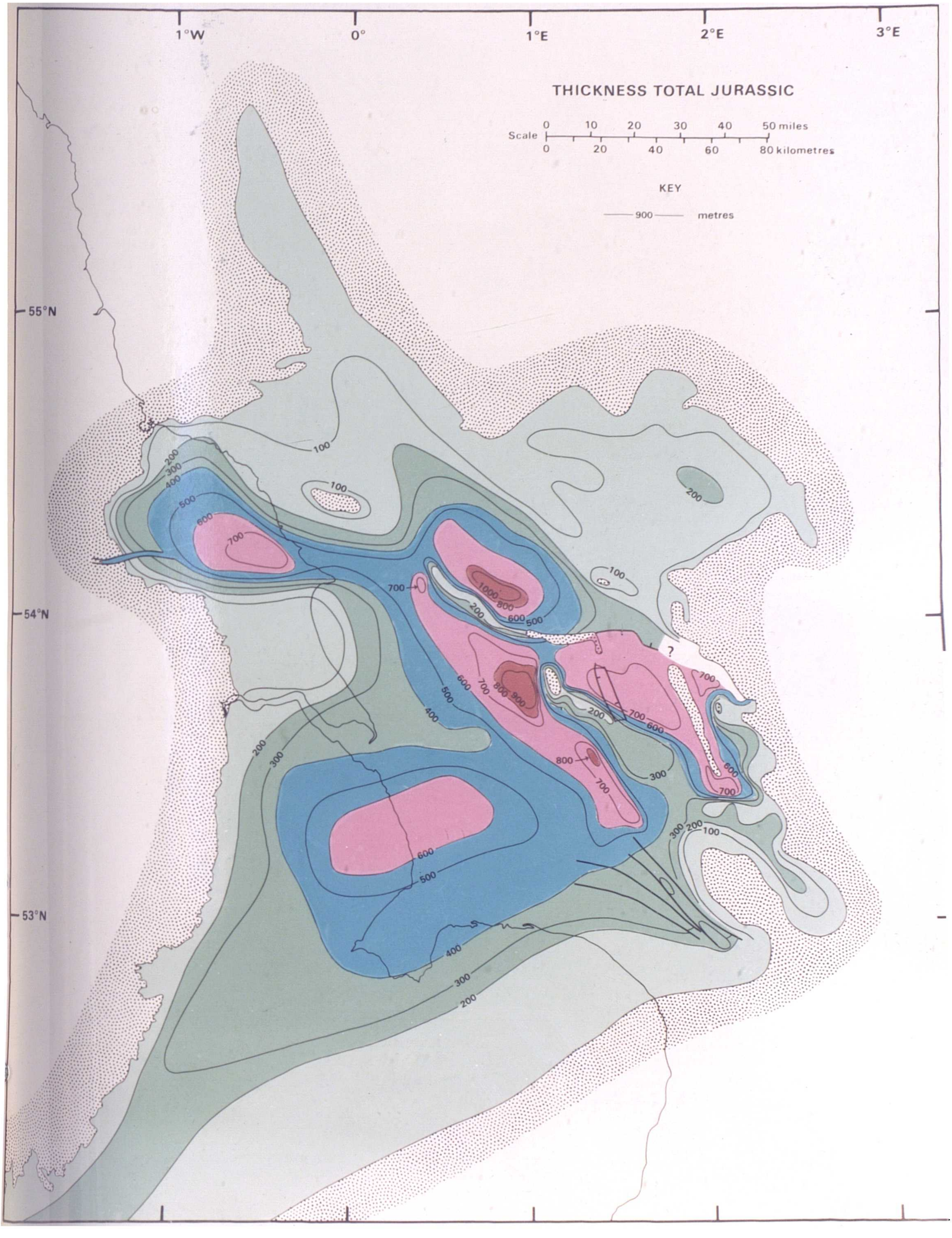


Figure 3. 2 Thickness of total Jurassic.

Jurassic strata are known to outcrop in two major areas within the offshore basin. The most extensive outcrops occur at seabed off the Yorkshire coast (Figure 1.3) and were originally described by Dingle (1971). Subsequent surveys by the BGS have extended and refined this early survey work in the area (Lott 1985, 86). The strata at outcrop and proved by seabed sampling and shallow core drilling range from Rhaetian to Kimmeridgian in age and lithologically and biostratigraphically compare closely with the succession onshore in the Cleveland Basin of north east Yorkshire (e.g. Cox et al. in prep.).

The second extensive outcrop of Jurassic strata within the offshore area is along the north-west to south-east trending Sole Pit Inversion structure (Figure 1.3). Here Jurassic strata ranging from Hettangian to Kimmeridgian in age have been proved at outcrop, usually beneath a thin Quaternary cover (Crosby 1984).

The greatest development of Jurassic strata (950m+), preserved in the offshore area, occurs along the present western margin of the Sole Pit Inversion Structure, and in the rim-synclines associated with the major salt structures commonly found within the Basin (Figure 3.2). These Zechstein salt structures began moving in Middle Triassic times (Brunstrom and Walmsley 1969) and continued to develop spasmodically throughout the Jurassic and subsequently until at least Late Pleistocene times. The subsidence patterns developed by these salt movements appear to have exerted a considerable influence on sedimentation patterns during the Jurassic.

The present limits of the Jurassic subcrop within the basin are the results of extensive tectonic inversion and a long period of erosion affecting the North Sea basin during the Late Jurassic - Early Cretaceous.

3.3. Subdivision of the sequence

The Jurassic strata of the southern North Sea have been divided into three major lithostratigraphic units , the Lower Jurassic or Lias Group, the Middle Jurassic or West Sole Group, and an Upper Jurassic or Humber Group(Rhys 1974). Subdivision of the sequence has to rely on using a combination of geophysical log correlation techniques and rock cuttings descriptions. The Borehole Compensated Sonic Log (BHCS) and Gamma Ray (GR) logs have proved particularly valuable in this respect (see Chapters 1 and 4).

The tripartite subdivision of the Jurassic succession in the offshore area though still valid may be further refined using more recently released well data and as a result of geological and geophysical surveys carried out by the BGS. A rexamination of the sequence using this new data in combination with correlation between recent cored and geophysically logged boreholes from eastern England, has allowed an improved lithostratigraphy for the offshore area to be developed and a clearer definition of the original unit boundaries as suggested by Rhys (1974) (Chapter 4).

The Jurassic strata of the Basin rest with apparent conformity on Rhaetian strata both in the offshore area and over most of its onshore outcrop. Figure 3.1 shows a structure contour map of the base of the Jurassic, based upon deep seismic data and is modified from Day et al. (1981). An examination of the distribution and thickness of these Rhaetian sediments (Fig. 2.1), which in the offshore area form the Winterton Formation, suggests that the patterns of differential subsidence which dominated much of the Basin during the Jurassic were already in operation by the Late Triassic. The Winterton Formation as defined by Rhys(1974) comprises an uppermost unit of pale greenish grey , dolomitic blocky mudstones and a lower unit of black fissile shales with variably developed sandstone interbeds. The upper two units of the formation are recognisable

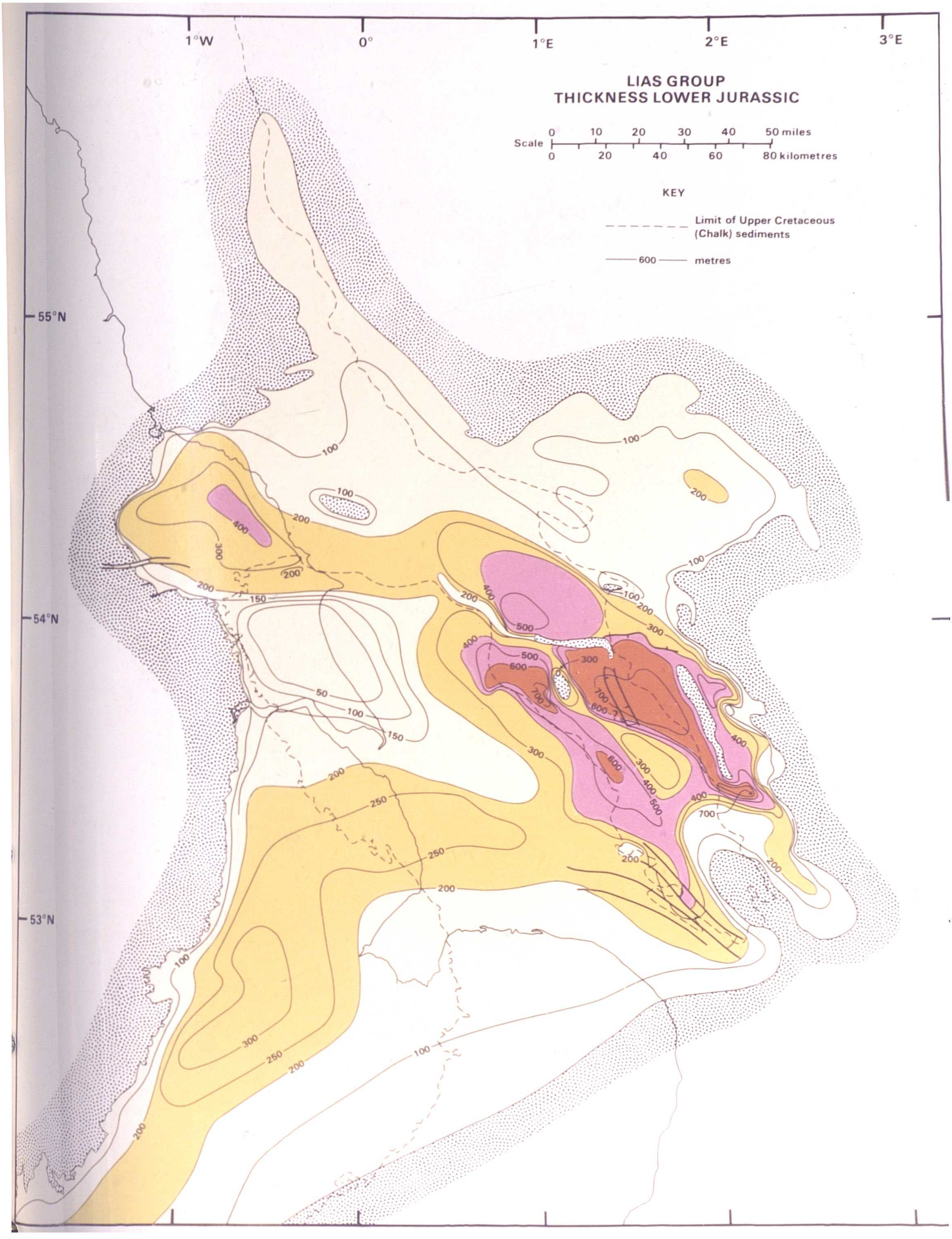


Figure 3.3 Thickness of Lias Group - Lower Jurassic.

over much of the area (Chapter 2). The top of the Winterton Formation is well defined by the development of a thin but persistent limestone unit at the base of the overlying Lias Group. The present limits of the Formation are defined in the offshore area by erosion of the basin margins. There is therefore no firm evidence for the subsequent overstep of Rhaetian strata by Jurassic sediments as occurs on the northern flank of the Anglo-Brabant Massif (Donovan et al. 1979) and therefore the original depositional limits of the formation, particularly along the Mid-North Sea High area remain difficult to define.

3.4. Lias Group

The Lias Group in the offshore area is defined by Rhys (op. cit.) as a unit that is equivalent to the Lias of the onshore area. This rather loose definition is taken to include Hettangian to Early Toarcian strata predominantly in a mudstone and argillaceous limestone facies. The base of the Group, as discussed earlier, is taken at the base of a laterally persistent limestone unit probably equivalent at least in part to the Hydraulic Limestones of the eastern England Lower Jurassic sequence (cf. Kent 1980). This basal limestone unit is generally 10 - 15m. in thickness and is one of a number of thin but extensive lithological units which can be recognised, within the Lias Group, from their log responses throughout the basin. Lithological variations within the Lias Group of the offshore area are largely restricted to changes in carbonate and silt content with the exception of the Frodingham Ironstones which are a very localised facies development not seen in wells offshore. The most prominent geophysical marker on the log responses lies at approximately the level of the Middle Lias, Marlstone Rock Bed (Rhys 1974).

In a recent lithostratigraphic subdivision of the Lias sequence in the Cleveland Basin Powell (1984) recognised five broad subdivisions of the

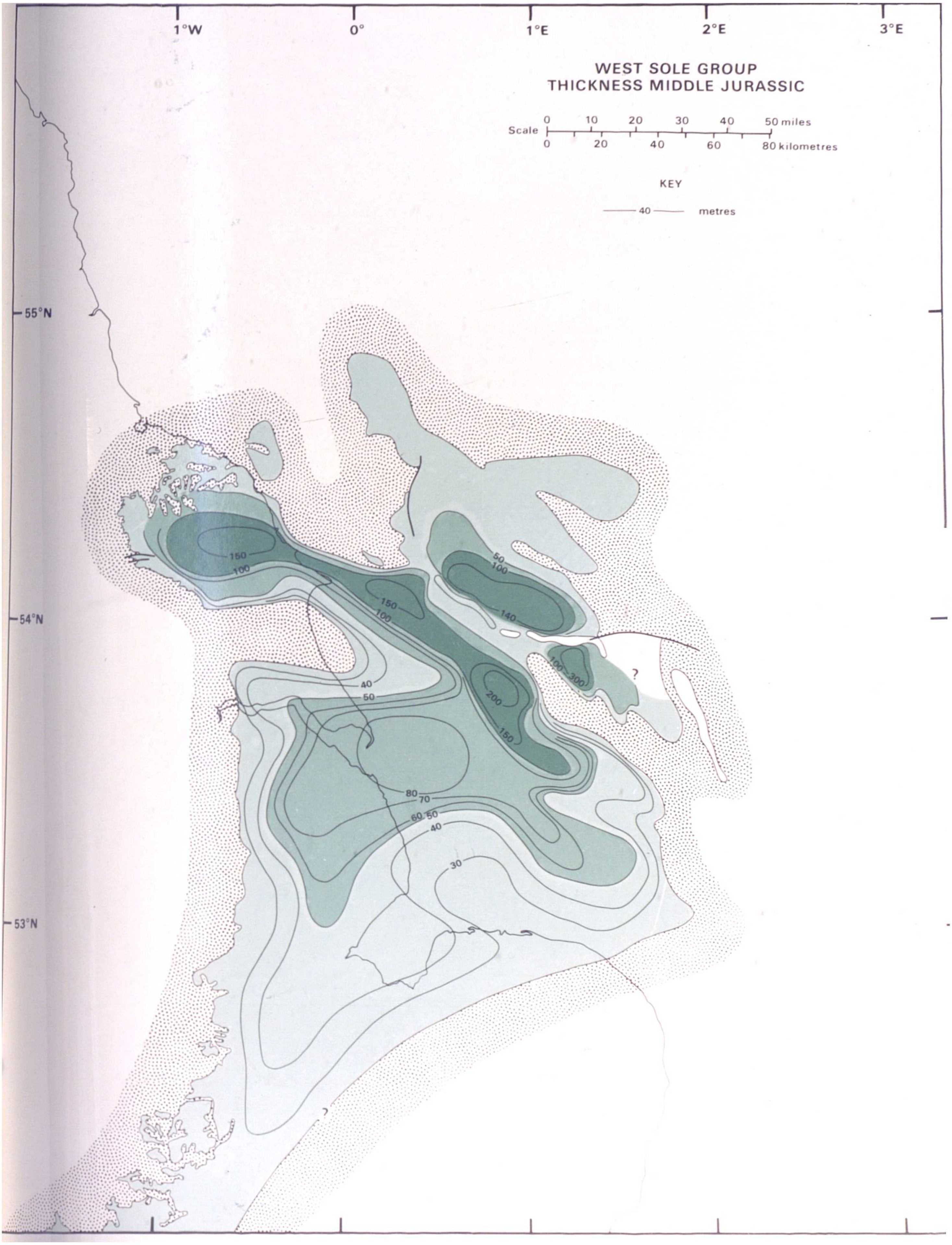


Figure 3.4 Thickness of West Sole Group - Middle Jurassic.

sequence; a thick lower mudstone and siltstone unit, the Redcar Formation, two thin middle units comprising more regressive fine grained sandstones and siltstones, the Staithes Formation, and an oolitic sandy ironstone, the Cleveland Ironstone Formation. Overlying these regressive units is an upper mudstone and siltstone unit of very variable thickness, the Whitby Mudstone Formation. The topmost unit recognised in the Cleveland Basin, the Blea Wyke Sandstone Formation (Knox 1984) is geographically limited in the extent of its outcrop in the onshore area. There is at present no firm evidence that this formation extends offshore, but the thick clastic ?Middle Jurassic successions in the Sole Pit Trough and in the rim synclinal areas may include a Late Toarcian component. These subdivisions which can be recognised both from lithological evidence in cores, at outcrop and from their log responses, can be recognised over much of the offshore area in the Lias Group, only the separation of the Staithes and Cleveland Ironstone Formations presents any problems. Powell (1984) also emphasises the presence of a number of laterally persistent thinner lithological units in the Whitby Mudstone Formation and correlations within the offshore basin suggest that some at least of these units may be traced offshore e.g. Jet Rock Member. A more detailed lithostratigraphic subdivision, in the offshore area, of the Lias Group has been made (Chapter 4) which again emphasises the lateral persistance of lithological units in the Group.

In the offshore area the top of the Lias Group is readily defined by the abrupt change to the shallow marine and brackish water sands and limestones of the Middle Jurassic, West Sole Group. The boundary is a prominent lithological change reflected both on log responses and in shallow seismic reflection profiles. The topmost strata of the Lias Group (equivalent to the Whitby Mudstone Formation and locally the Blea Wyke

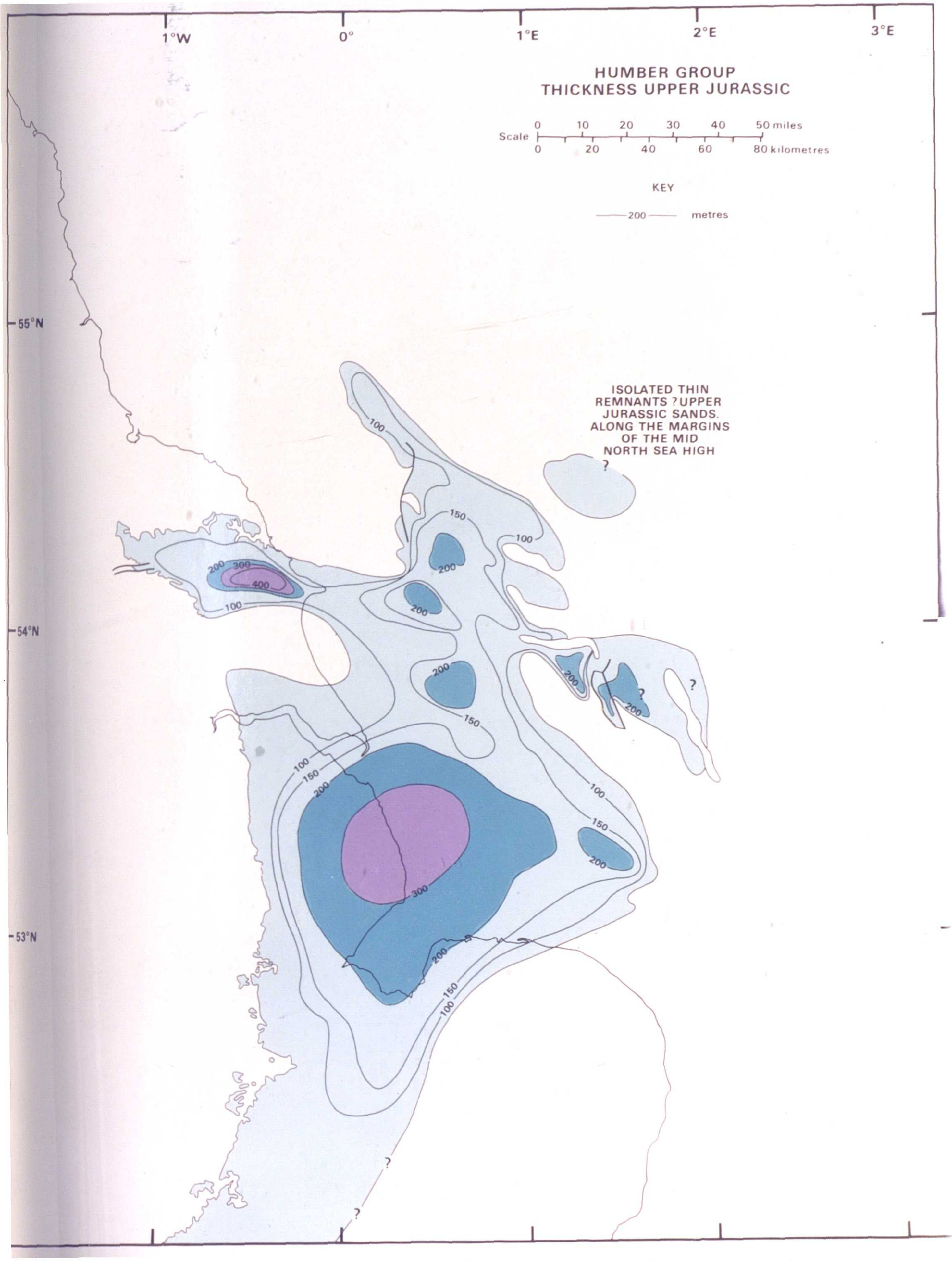


Figure 3.5 Thickness of Humber Group - Upper Jurassic.

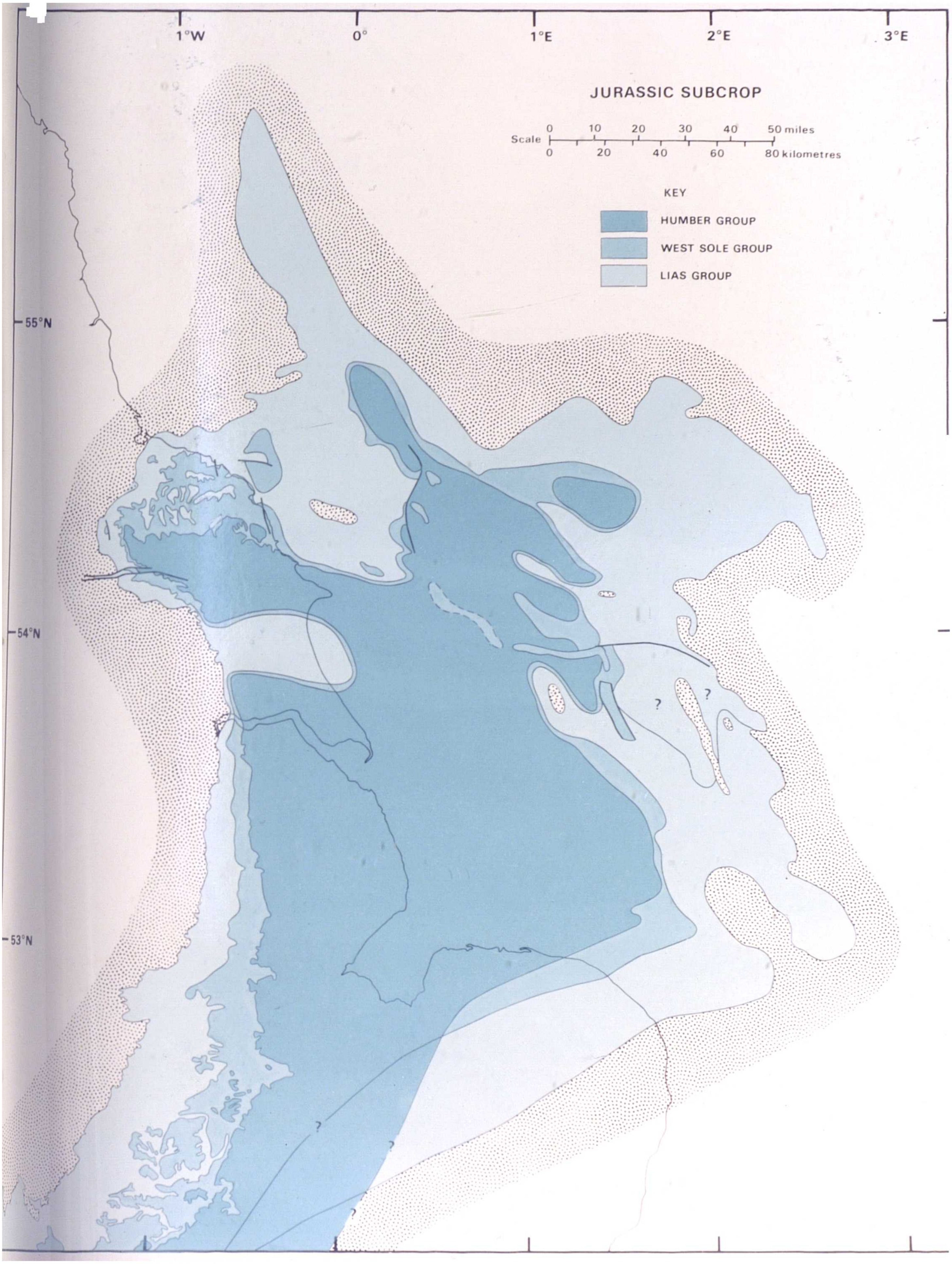


Figure 3.6 Jurassic subcrop.

Formation of Powell (1984) and Knox (1984), show considerable variations in thickness over the Basin. This is a reflection of the widespread phase of tectonism and erosion in pre-Aalenian times (e.g. Hemingway 1974). A single cored borehole drilled off the north east Yorkshire coast proved Middle Jurassic sideritic mudstones and carbonaceous sandstones (?Saltwick Formation) resting on Lias strata of Early Toarcian age (borehole 81/42,Figure 9.4).

3.5. West Sole Group

The West Sole Group only broadly corresponds to the Middle Jurassic as currently defined (Cope et al. 1980). The Group includes strata ranging from Aalenian to Callovian in age (Rhys 1974). The thickness and present distribution of the Group is presented in Figure 3.4. The base of the Group is a well defined lithological change in the majority of wells which penetrate the junction. However, as pointed out by Rhys (op. cit.) the Group may include beds which are of Late Toarcian age i.e. the Blea Wyke Sandstone Formation which are lithologically, in cuttings material at least, difficult to distinguish from the overlying sandstone sequences of the Middle Jurassic proper.

The considerable facies changes that occur within the Middle and Upper Jurassic successions of Eastern England from north to south across the basin (Figures 3.7, 4.6) (Kent 1980a) make the definition of the upper boundary of the Group more difficult. Wells drilled on the comparatively stable East Midlands Shelf area (Figure 4.1) can be quite readily correlated with the onshore sequences of Lincolnshire and South Yorkshire using geophysical log responses and the limited core data available. The sequence shows a gentle eastward thickening of the main lithostratigraphic subdivisions e.g. Lincolnshire Limestone Formation and Upper Estuarine Series. However these units are then less readily defined in the markedly

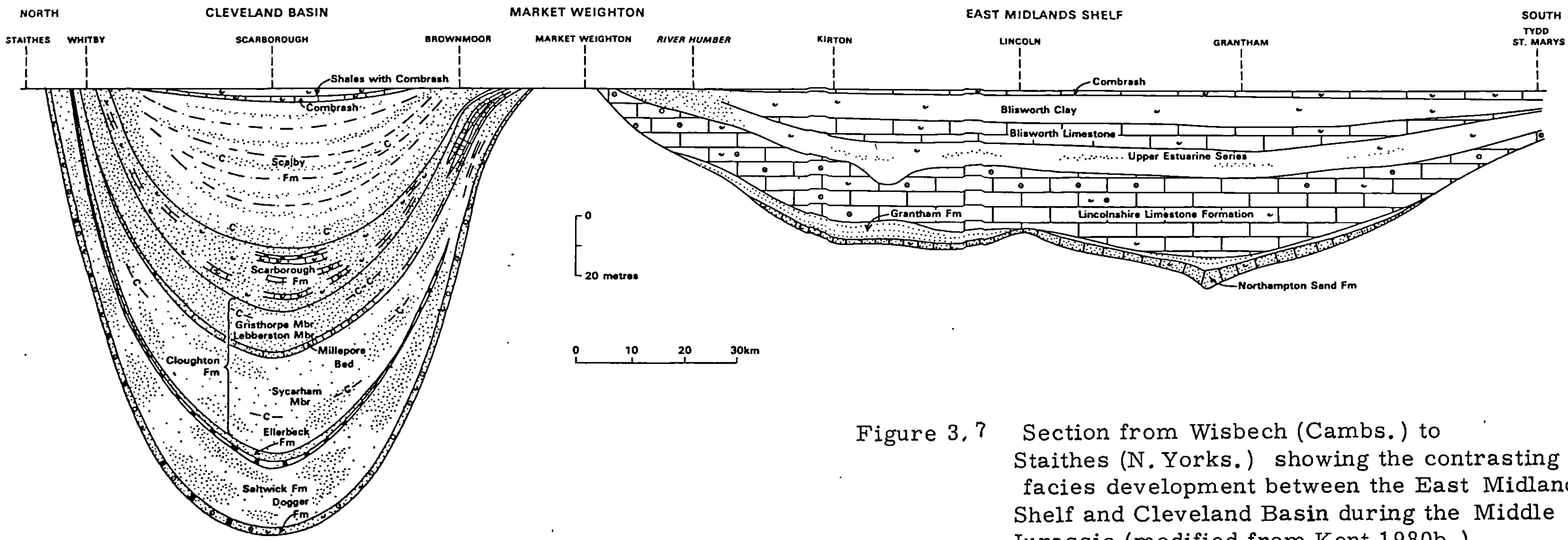


Figure 3.7 Section from Wisbech (Cambs.) to Staithes (N. Yorks.) showing the contrasting facies development between the East Midlands Shelf and Cleveland Basin during the Middle Jurassic (modified from Kent 1980b.)

thicker Middle Jurassic successions of the Sole Pit Trough which show more affinity with the Cleveland Basin sequence in terms of thickness and facies. The present palaeontological definition of the Middle / Upper Jurassic boundary at the base of the Oxfordian (Cope et al. 1980), while readily applicable in most cored and outcrop sequences with good palaeontological control, is less suitable for the uncored offshore succession particularly as the boundary lies within a lithologically uniform sequence, the Oxford Clay Formation. Without, therefore, considerably more cored material from the offshore area this boundary is unlikely to be precisely defined. The more useful break in these offshore sequences is the lithological change, close to the Middle /Upper Jurassic boundary, represented by the junction between the sandy Kellaways Beds and the Oxford Clay. This thin but persistent sandy unit is traceable from the Dorset to Yorkshire coasts and has been proved in seabed samples (Enclosure 1) from offshore north-east Yorkshire. In addition this unit, which is traceable without any significant facies change, forms a prominent geophysical marker on the downhole logs. The top of the Kellaways Rock and Sand unit is therefore taken , for the purpose of this suite of maps as the top of the West Sole Group and approximates to the top of the Middle Jurassic (Chapter 4).

3.6. Humber Group

The Humber Group as defined by Rhys (1974) includes three Formations, a lower shale unit, the Oxford Clay Formation, a middle limestone and sandstone unit, the Corallian Formation and an upper unit of shales, the Kimmeridge Clay Formation. The present-day distribution and thickness of the Humber Group is shown in Figures 3.5, 3.6. The base of the Humber Group, which as discussed above is taken as the top of the Kellaways Rock and Sand unit, equates with the base of the Group as originally defined by Rhys (op. cit.). Within the Humber Group, as with the West Sole Group,

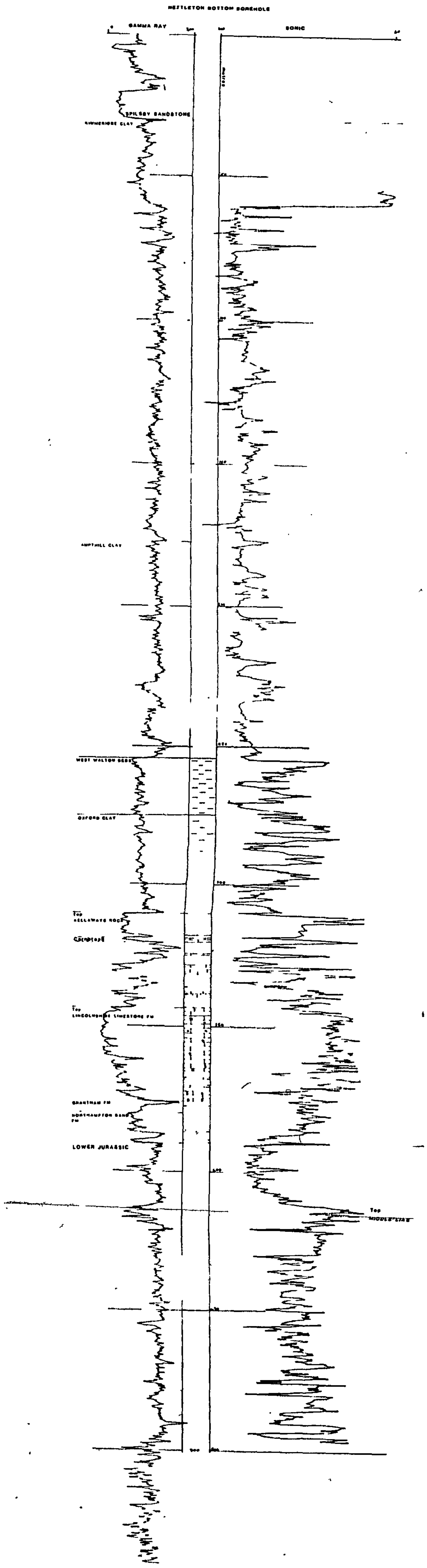


Figure 3.8 Summary log of the Nettleton Bottom borehole with Gamma Ray and Sonic log profiles.

there is considerable facies change from north to south across the basin (Figure 4.6;cf. Kent 1980b). The Humber Group lithologically shows some affinities with both the Upper Jurassic succession of the Cleveland Basin (Cox et al. in prep) and of the East Midlands area. The Oxford Clay is for example poorly developed both in the Cleveland Basin and in the northern part of the Sole Pit Trough but thickens southwards into the East Midlands Shelf area. There is in addition, in the Sole Pit Trough and generally over the northern part of the U.K. sector, a prominent development of spiculitic sandstone and oolitic limestones of Oxfordian age (Figure 4.9). These beds were termed by Rhys (op. cit.) the Corallian Formation which equates largely with the Lower Calcareous Grit, Coralline Oolite and Upper Calcareous Grit Formations of the onshore Cleveland Basin area (Cope et al. 1980). Overlying this formation within the offshore area are thinly developed Ampthill Clays and thick shales of the Kimmeridge Clay Formation. The Kimmeridge Clay Formation has been extensively sampled in the offshore area and the sequence is known to correlate well with the onshore outcrops (Chapter 6; Cox et al. in prep.).

In contrast wells drilled through the Humber Group on the East Midlands Shelf show good correlations with the Upper Jurassic sequences from Lincolnshire and South Yorkshire. Over this Shelf area there is an obvious subdivision into a lower predominently clay unit largely equivalent to the Oxford Clay Formation, a middle unit that is more calcareous and silty with a prominent log response, equivalent to the West Walton Beds (which lithostratigraphically therefore should be included in the Corallian Formation) and an upper clay unit, the Kimmeridge Clay Formation representing the Ampthill and Kimmeridge Clays (Chapter 4).

The Upper Jurassic / Cretaceous boundary in eastern England lies within the Spilsby Sandstone sequence (Cope et al. 1980). This boundary, which is

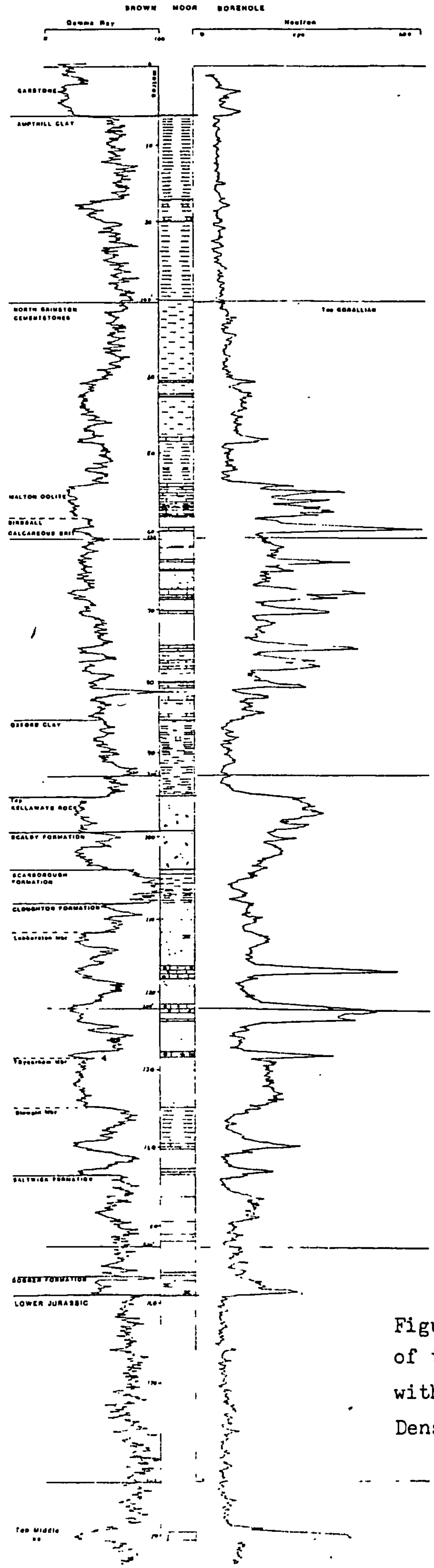


Figure 3.9 Summary log of the Brown Moor borehole with Gamma Ray and Neutron Density log profiles.

there is considerable facies change from north to south across the basin (Figure 4.6;cf. Kent 1980b). The Humber Group lithologically shows some affinities with both the Upper Jurassic succession of the Cleveland Basin (Cox et al. in prep) and of the East Midlands area. The Oxford Clay is for example poorly developed both in the Cleveland Basin and in the northern part of the Sole Pit Trough but thickens southwards into the East Midlands Shelf area. There is in addition, in the Sole Pit Trough and generally over the northern part of the U.K. sector, a prominent development of spiculitic sandstone and oolitic limestones of Oxfordian age (Figure 4.9). These beds were termed by Rhys (op. cit.) the Corallian Formation which equates largely with the Lower Calcareous Grit, Coralline Oolite and Upper Calcareous Grit Formations of the onshore Cleveland Basin area (Cope et al. 1980). Overlying this formation within the offshore area are thinly developed Ampthill Clays and thick shales of the Kimmeridge Clay Formation. The Kimmeridge Clay Formation has been extensively sampled in the offshore area and the sequence is known to correlate well with the onshore outcrops (Chapter 6; Cox et al. in prep.).

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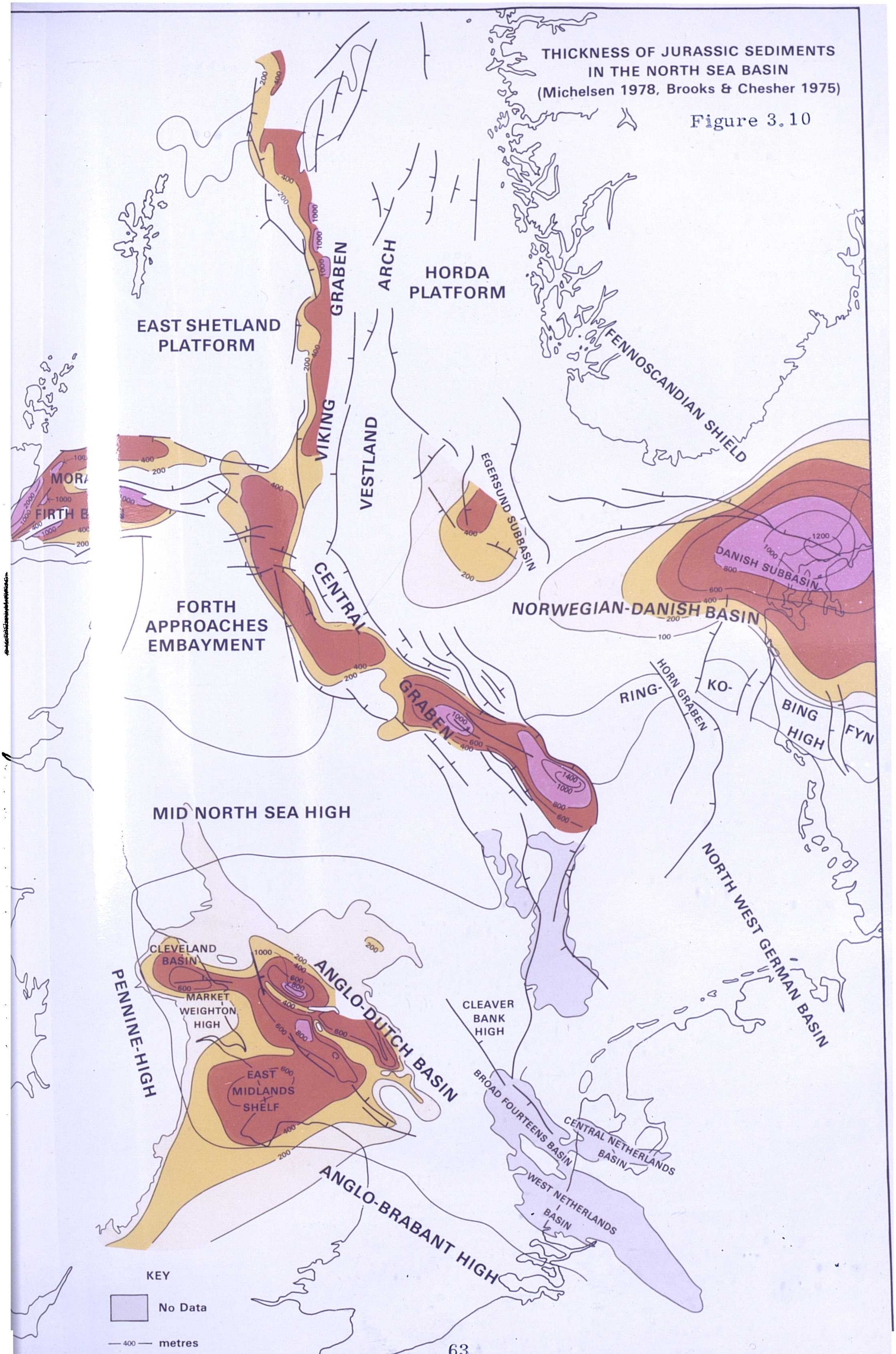
The Upper Jurassic / Cretaceous boundary in eastern England lies within the Spilsby Sandstone sequence (Cope et al. 1980). This boundary, which is defined largely on palaeontological criteria, is not recognisable offshore because of the lack of cored material. For the purpose of this series of maps therefore the top of the Jurassic succession i.e. top of the Humber Group, is taken as the top of the argillaceous Kimmeridge Clay formation. Over the East Midlands Shelf this boundary is coincident with th Kimmeridge Clay / Spilsby Sandstone junction and lithological change, while off the Yorkshire coast this boundary, because of the absence of any sandy developments, is represented by the Kimmeridge Clay / Speeton Clay junction. The latter though not a marked lithological change is still recognisable on log responses in the few wells that have been drilled through the junction. On shallow seismic profiles this junction is often seen as a low angled unconformity (Chapter 9). The Jurassic /Cretaceous boundary has been cored in a single BGS borehole 81/43 and details of the stratigraphy of the sequence are included in Chapter 7 and Lott et al. (in press).

3.7. Conclusions

The Jurassic succession of the U.K. sector of the Southern North Sea Basin is an erosional remnant of a much more extensive Jurassic depositional basin. The Jurassic sediments preserved in the offshore area may be many times thicker than the sequences known from onshore in eastern England. The maximum preserved thickness so far proved in the U.K. sector is c.950m, this compares with >2000m in the West Netherlands Basin, c.1200m in the Norwegian - Danish Basin, >1400m in the Central Graben and c.1000m in the Viking Graben (Figure 3.10). It is worth noting that in the U.K. sector much of the commercial drilling has been restricted to more positive structural features and it is therefore probable that the thickest Jurassic successions have yet to be drilled.



THICKNESS OF JURASSIC SEDIMENTS
IN THE NORTH SEA BASIN
(Michelsen 1978, Brooks & Chesher 1975)
VIKING GRABEN
VESTLAND ARCH
HORDA PLATFORM
EAST SHETLAND PLATFORM
FENNOSCANDIAN SHIELD
MORAY FIRTH BASIN
EGERSUND SUBBASIN
CENTRAL GRABEN
DANISH SUBBASIN
NORWEGIAN-DANISH BASIN
FORTH APPROACHES EMBAYMENT
RING-KO-BING-FYN HIGH
HORN GRABEN
MID NORTH SEA HIGH
NORTH WEST GERMAN BASIN
CLEVELAND BASIN
MARKET WEIGHTON HIGH
ANGLO-DUTCH BASIN
PENNINE-HIGH
CLEAVER BANK HIGH
EAST MIDLANDS SHELF
BROAD FOURTEENS BASIN
CENTRAL NETHERLANDS BASIN
WEST NETHERLANDS BASIN
ANGLO-BRABANT HIGH
KEY
No Data
400 metres

Figure 3.10

CHAPTER 4

The lithostratigraphy of Jurassic sediments in the U.K. sector of the Southern North Sea Basin.

The lithostratigraphy of Jurassic sediments in the U.K. sector of the Southern North Sea Basin.

4.1. Introduction

The Jurassic sediments of the U.K sector of the Southern North Sea Basin have only previously been described in very broad terms (Kent 1967, 1980a & b). The first lithostratigraphical subdivision of the Jurassic sequence was published by Rhys (1974). Each lithostratigraphic unit described was defined using a combination of rock cuttings and wireline geophysical log information. This lithostratigraphic scheme for the Jurassic was necessarily broad because of limitations on both the release of well data and because of a general lack of interest in the non-prospective Jurassic sequence south of the Mid-North Sea - Ringkobing-Fyn high.

The purpose of this paper is threefold. Firstly to provide an update on the 1974 lithostratigraphic scheme, based upon the subsequent release of more recent wells. Secondly to more fully describe the Jurassic succession of the U.K. sector by an integration of the commercial data with shallow core and sample data collected by the BGS within the basin. Thirdly to relate the Jurassic sequences to adjacent basins.

4.2. Lias Group- Lower Jurassic

The Lower Jurassic sediments of the Southern North Sea Basin predominantly comprise a sequence of marine shales and argillaceous limestones disconformably overlying the thin, transgressive, brackish and marginal marine shales and sandstones of the Late Triassic Winterton Formation. These Lower Jurassic sediments range from Hettangian to Early Toarcian in age and can be divided, on the basis of their geophysical log character, into six lithostratigraphic units (LJ1-LJ6) which can be widely traced between commercial wells drilled in the basin. The boundary of each unit is defined by a sharp change in lithology and consequently in log response. The Gamma Ray and Borehole Compensated Sonic Logs were used because of their widespread availability over the basin.

Thickness variations within the Lias Group in the ofshore area are considerable (Chapter 3). The greatest thickness so far proved in the U.K. sector was found in Well 49/16-5 (Conoco) where 744m of Lower Jurassic mudstones and argillaceous limestones were proved. A similar thickness has been proved in wells drilled in the West Sole Gasfield area (e.g. 48/6-5 B.P.) where 709m of Lower Jurassic sediments were penetrated. These thickness variations are a reflection of differential subsidence patterns within the basin which result from reactivation of structural lineaments established in Permian times (Chapter 1).

4.2.1. Unit LJ 1 Unit LJ1 is the basal unit of the Lower Jurassic sequence. The unit comprises a sequence of hard, argillaceous limestones which immediately overly the low velocity shales of the upper part of the underlying Winterton Formation. The geophysical log profile is typically a low gamma ray response together with a high velocity , spiky sonic response. The unit can be traced onshore into the East Midlands area where it is known as the 'Hydraulic Limestones' and there consists of a sequence of alternating shales and shelly argillaceous limestones of Early Hettangian age (Kent 1980b). The unit represents the establishment of fully marine conditions within the basin following the Late Triassic (Rhaetian) transgression.

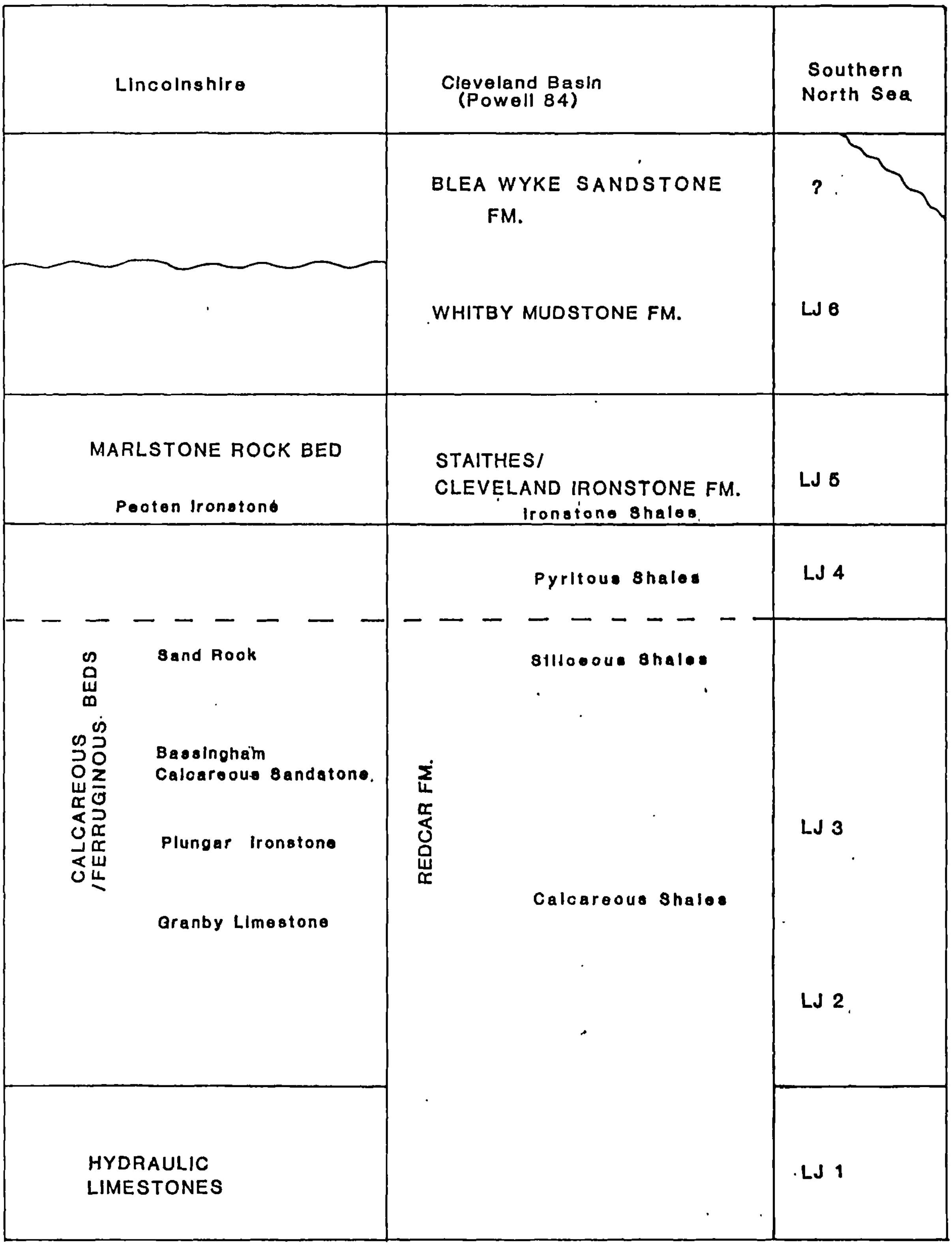


Figure 4.1 Lithostratigraphy of the Lower Jurassic.

4.2.2. Unit LJ 2

This unit is defined by an increase in the gamma ray response from the underlying unit and a corresponding decrease in the sonic velocity. The unit comprises thin argillaceous limestones interbedded with shales.

4.2.3. Unit LJ 3

There is an abrupt increase in the proportion of limestone beds in this unit and this is reflected in the spiky character of the sonic velocity profile. The background gamma reponse is not significantly different from that of the underlying unit LJ 2. Unit LJ 3 is likely to equate with the widely mapped interval of calcareous beds known from onshore outcrops as the **"Calcareous Shales"**. Within the unit a number of minor cycles can be distinguished showing a transition upwards from carbonate poor to carbonate rich horizons. Over the East Midlands Shelf these minor cycles may range up to 30m in thickness and are of considerable areal extent.

4.2.4. Unit LJ 4

Unit LJ 4 is characterised by a comparatively high gamma ray / low sonic response with medial low gamma / high sonic, carbonate rich interval. The lower boundary of the unit is marked by an abrupt change to the limestone rich interval of unit LJ 3, with its consequent high sonic velocity profile.

4.2.5. Unit LJ 5

Unit LJ 5 is of particular interest as it contains two important marker horizons of the Lower Jurassic . In the upper part, the unit shows a high sonic velocity / low gamma interval, which an examination of cuttings material shows to consist of locally oolitic, ferruginous or sandy beds which are likely to equate with the **Marlstone Rock Bed** (in Lincolnshire) and the **Cleveland Ironstone and Staithes Formations** (in the Cleveland Basin) of Late Pliensbachian age (Powell 1984; Chapter 3). This interval is

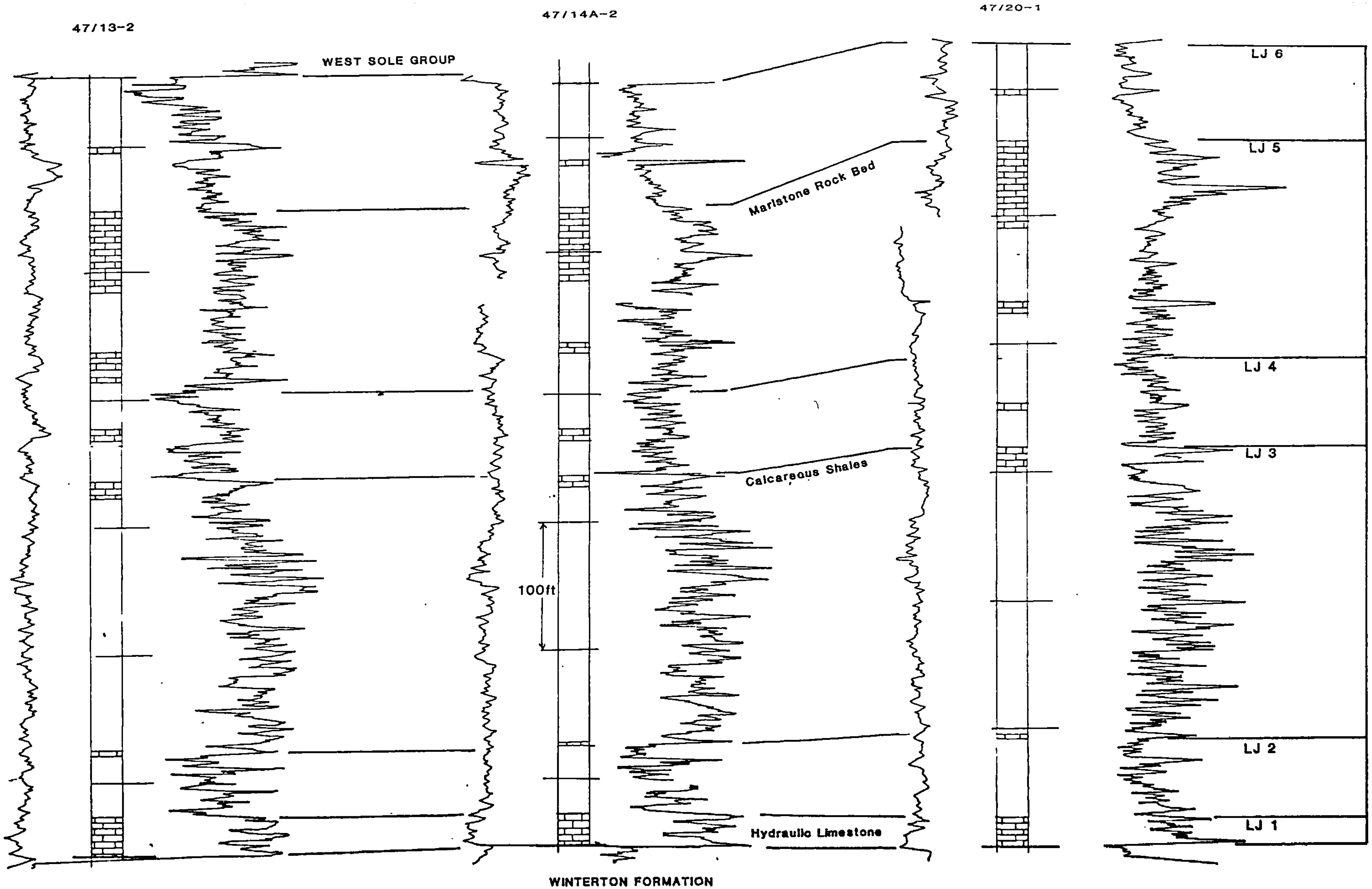
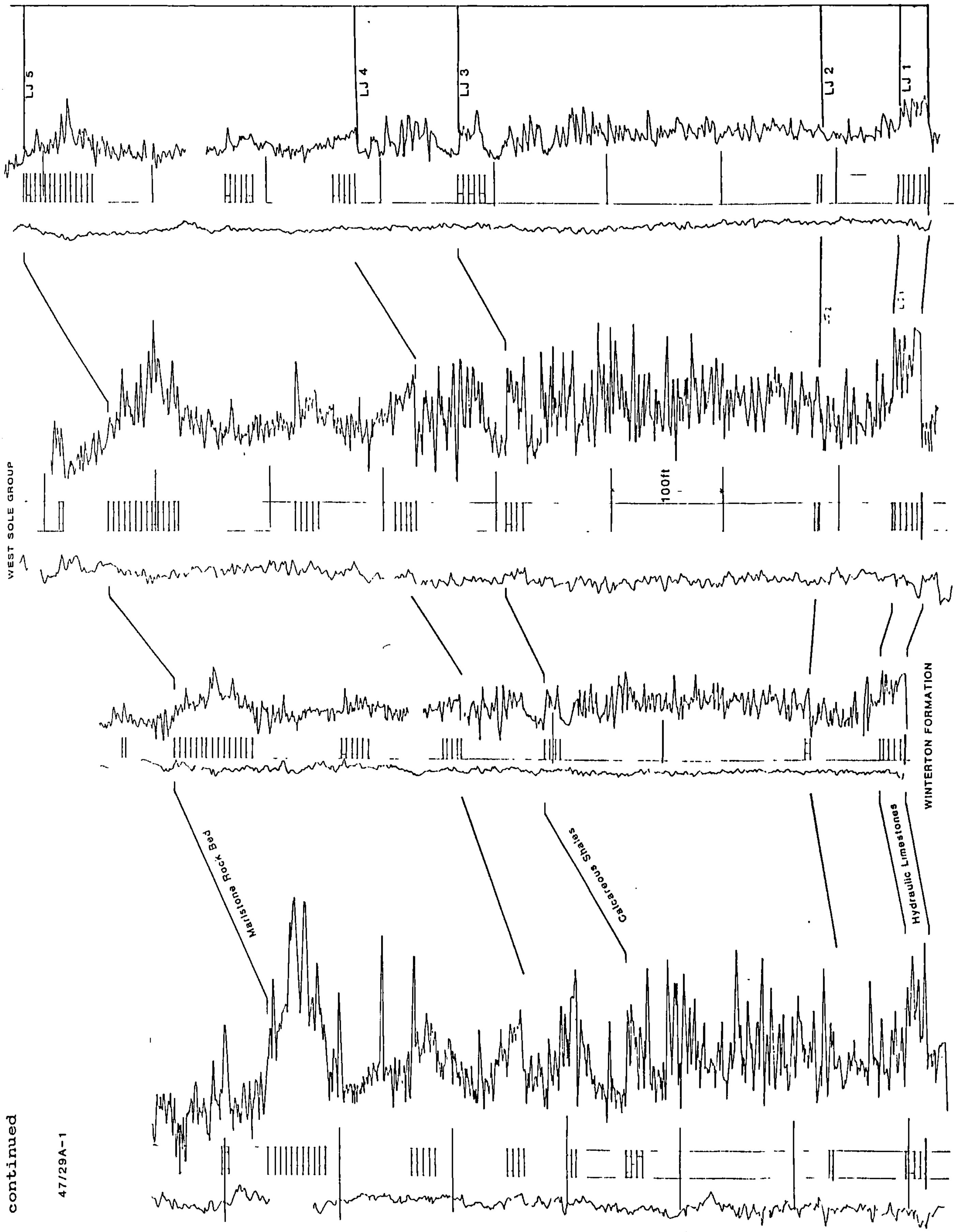


Figure 4.2 Lithostratigraphic correlation of selected wells from the Lias Group.


continued
47/29A-1
LJ 5
LJ 4
LJ 3
LJ 2
LJ 1
WEST SOLE GROUP
100ft
Marlstone Rock Bed
Calcareous Shales
Hydraulic Limestones
WINTERTON FORMATION

widely recognisable within the U.K.sector of the basin and a correlation with a similar regressive late Pliensbachian sequence recognised in the Dutch Sector (West Netherlands Basin) seem likely (NAM / RGD 1980).

In the lower part of unit LJ 5 a second high velocity / low gamma interval possibly represents, from correlation with the East Midlands area, the equivalent of the **Pecten Ironstone** (Early Pliensbachian). The unit LJ 5 therefore, shows a distinctive 'waisted' gamma / sonic profile over much of the basin and which is particularly well developed in the East Midlands Shelf sequences (Figure 4.2).

4.2.6. Unit LJ 6

This unit is of variable thickness across the U.K. sector, largely as a consequence of a phase of pre-Aalenian tectonics and erosion over the basin. The unit shows a characteristic decrease in sonic velocity when compared with the underlying unit, though a thin high velocity sonic spike probably equivalent to the organic rich **Jet Rock Member** (Powell 1984) occurs just above the base of the unit. The unit is largely composed of calcareous shales which are equivalent to the Whitby Mudstone Formation of Powell (1984) and are of probable Early Toarcian age. It is not yet possible using either log responses or cuttings material to distinguish Late Toarcian sediments of the Blea Wyke Formation (Knox 1984) in the U.K.sector.

4.3. Lower Jurassic sediments in adjacent basins.

4.3.1. West Netherlands Basin (Heybroek 1975; NAM / RGD 1980)

Lower Jurassic sediments in the West Netherlands Basin are closely comparable in lithology to those of the U.K. sector. The Lower Jurassic sediments form part of the **Altena Group** (Rhaetian to Oxfordian), and are divided into a lower **Aalburg Shale Formation** (Hettangian to Pliensbachian) and an upper **Werkendam Shale Formation** (Toarcian to Bajocian). The junction

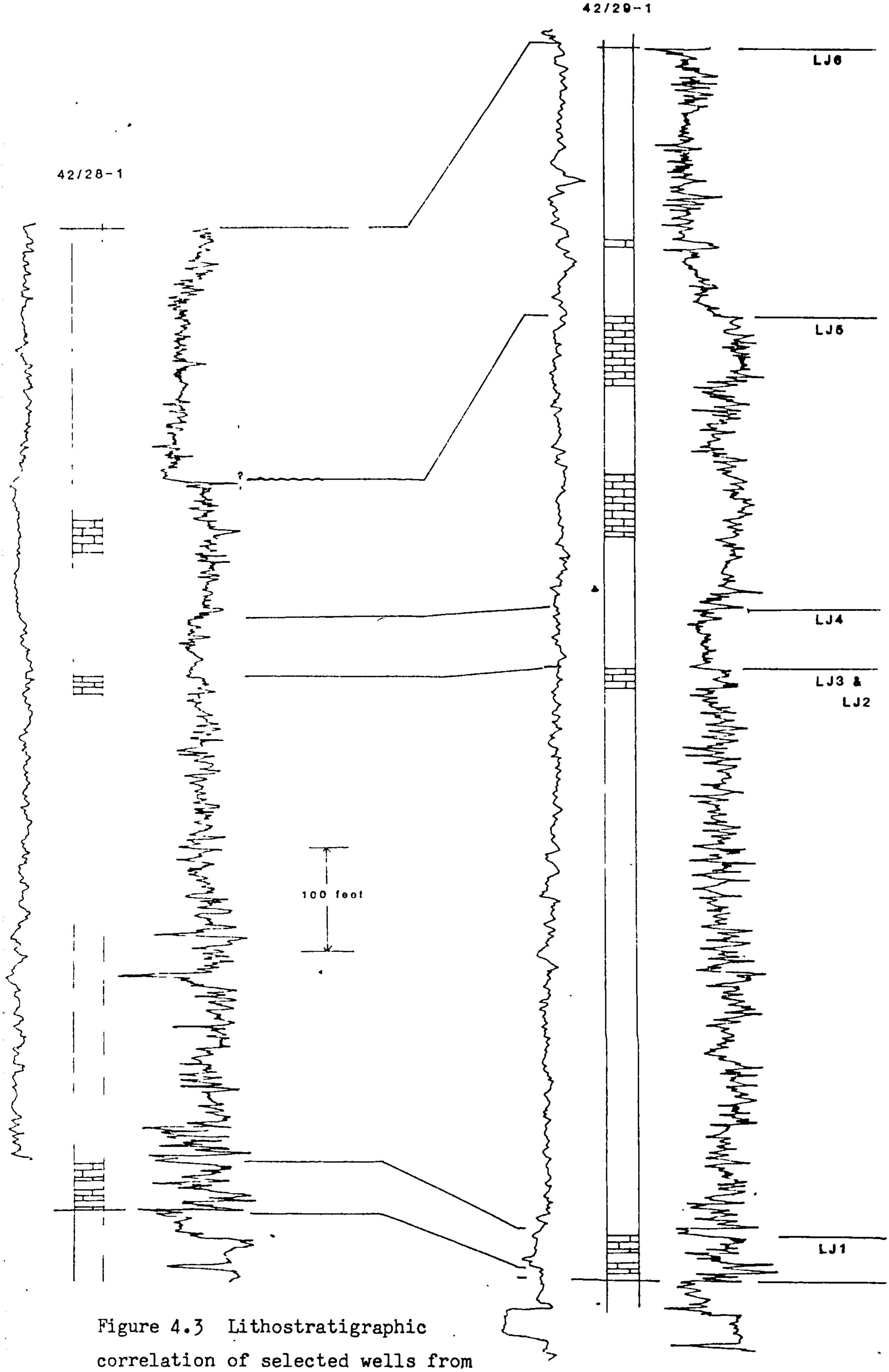


Figure 4.3 Lithostratigraphic correlation of selected wells from the Lias Group.

between the two formations is marked by the development of the bituminous **Posidonia Shale Member** of the Werkendam Shale Formation (equivalent in part to the Jet Rock Member, Unit LJ 6). This marine shale succession ranges from Hettangian to Bajocian in age. A probable correlative of the Marlstone Rock Bed is recognised with the development of a sandy, oolitic sequence at the top of the Aalburg Shale Formation.

4.3.2. Norwegian - Danish Basin (Michelson 1978, 1982; Vollset and Doré 1984)

Lower Jurassic strata are largely preserved in localised troughs within the basin and are known as the **Fjerritslev Formation.** The formation typically comprises dark grey, marine, calcareous shales and argillaceous limestones and ranges in age from Hettangian to Early Pliensbachian in the Danish Central Graben. More complete sequences are likely in the rim synclines associated *with Zechstein salt diapirs but, as yet have not been* drilled. In the main Norwegian / Danish Basin more complete Lower Jurassic marine shale sequences are present ranging from Hettangian to Toarcian in age.

4.3.3. Central and Northern North Sea (Deegan and Scull 1975; Brooks and Chesher 1975).

Lower Jurassic strata are largely absent from the Central Graben area, much of the sequence probably having been removed by erosion following the volcanic up-doming of the area during the Middle Jurassic (Eynon 1981). Further north in the Viking Graben the sequence has been divided into a lower arenaceous succession the **Statfjord Unit** (Rhaetian - Sinemurian) and an upper marine argillaceous sequence ,the **Dunlin Unit** (Hettangian to Early Bajocian). Links with the Southern North Sea Basin were probably maintained to the east of the Mid-North Sea High, via the Central Graben completing an extensive Lower Jurassic basinal area probably marking the greatest extent of the Jurassic seas over the North-West European craton (Zeigler 1982).

4.4. West Sole Group- Middle Jurassic

The Middle Jurassic (Aalenian to Callovian) sediments of the Southern North Sea Basin comprise a series of interbedded marine and brackish water shales, sandstones and limestones which reflect the constantly oscillating nature of the shoreline as shallow shelf seas transgressed and regressed across the basin. As a result of these eustatic sealevel movements (Hallam 1978) a distinct cyclic nature to the sedimentary facies in the area is apparent. The current stratigraphy of the Middle Jurassic successions of eastern England is summarised in Figure 4.6 and is largely based on Cope et al. (1980). In the absence of many good cored sequences from the Middle Jurassic of the offshore area geophysical log correlations to determine the lithostratigraphy of the sequence are particularly important. On the basis of log responses and cuttings information from commercial wells drilled in the area it is apparent that there is a distinct division into those wells drilled on the East Midlands Shelf area, which are of a similar thickness to and correlate lithostratigraphically with cored boreholes drilled onshore in Lincolnshire and south Yorkshire (Figure 4.5), and wells drilled further east and northwards in which the successions are considerably expanded and show more affinities with the Cleveland Basin Middle Jurassic sequence (Figure 4.7). In the existing lithostratigraphic subdivision of the Jurassic by Rhys (1974) no real attempt was made to subdivide the Middle Jurassic, although it was noted that it was possible in some wells to recognise Lincolnshire Limestone and Cornbrash type lithologies. From an examination of all the wells drilled through the Middle Jurassic of the Southern North Sea Basin it is apparent that the type well selected for the Middle Jurassic by Rhys (1974), 47/15-2, lies in an area transitional in facies between the East Midlands successions, dominated by interbedded marine oolitic limestones and calcareous sandstone units (e.g. 47/13-1, 47/15-2, Figure 4.4) and the thicker sandstone dominated successions of the Sole Pit Trough and rim synclinal areas of the offshore basin. It seems likely that those areas of comparatively rapid subsidence e.g. rim synclines and the Sole Pit trough acted as sumps which trapped much of the sediment derived from the Pennine - Mid North Sea High, therefore preventing the general inundation of the East Midlands Shelf area by detrital sediments (Figure 4.7). Correlation between the wells drilled in the offshore area of the East Midlands Shelf and the cored and geophysically logged boreholes of Nettleton Bottom and Brown Moor in Lincolnshire and south Yorkshire respectively, allow subdivision of the sequence into two primary units (**MJ 1 and MJ 2**). The log responses of both these units are characterised by an upward decrease in gamma response and increase in sonic velocity reflecting a cyclic upward transition from muddy sandstones to cleaner calcareous, cemented sands and limestones. The lower of these two lithostratigraphic units, **MJ 1**, comprises by reference to the Nettleton Bottom Borehole (Figure 3.8), the **Northampton Sand, Grantham and** Lincolnshire Limestone Formations, the latter, which comprises hard oolitic limestones, giving the distinctive low gamma / high velocity response that marks the top of the unit. The upper lithostratigraphic unit, **MJ 2**, comprises the clays and sandstones of the **Upper Estuarine Series and** Blisworth Clay capped by the sandstones of the **Kellaways Beds** (Figure 4.4).

In the East Midlands area there is known to be a regional disconformity beneath the Upper Estuarine Series and it is thought that a good part of the Bajocian and early Bathonian sequence is missing. It seems likely, therefore, that the thick Middle Jurassic succession of the Sole Pit Trough is a more complete Bajocian / Bathonian sequence than that known in the

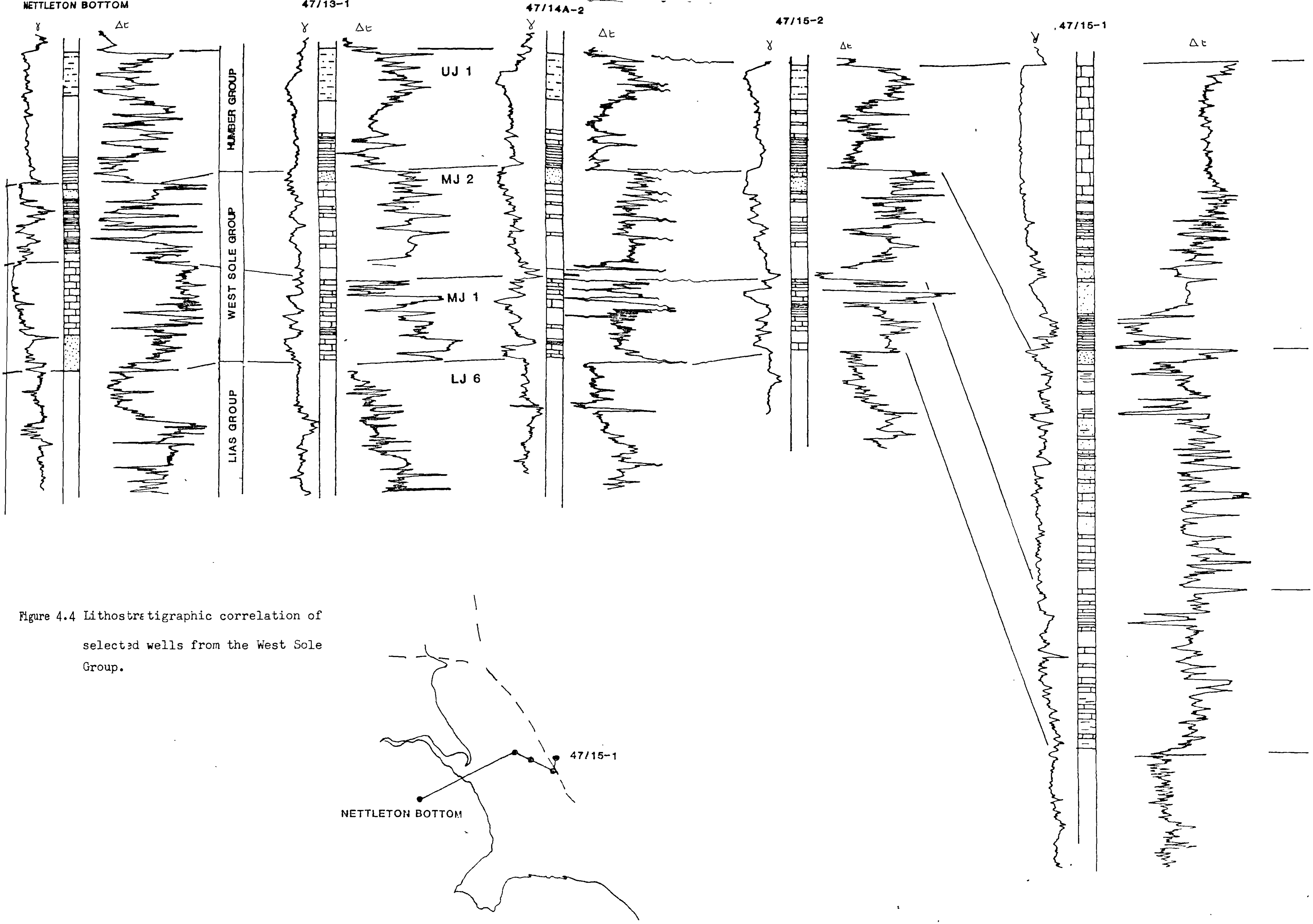


Figure 4.4 Lithostratigraphic correlation of selected wells from the West Sole Group.

East Midlands.

4.4.1. Unit MJ 1

The base of unit MJ 1 is characterised by a marked decrease in gamma ray response and increase in sonic velocity when compared with the underlying Lower Jurassic mudstones. In the Nettleton Bottom borehole (Figure 3.8) the lowermost beds of the unit consist of the marginal marine ferruginous sands and ironstones of the Northampton Sand Formation overlain by the brackish water clays and sands of the Grantham Formation. Above this sequence lies the limestone dominated succession of the Lincolnshire Limestone Formation. Cuttings material shows that the oolitic limestone facies of the formation extend some way offshore (Fig.4.7) but are gradually replaced eastwards by sandstone and shale dominated sequences. In the offshore area log responses suggest that this unit is probably equivalent to the Lincolnshire Limestone Formation; the Northampton Sand and Grantham Formations being only localised facies developments that do not extend far into the offshore area e.g. 47/13-1, 47/29A-1. The unit shows a sharp top on the log responses.

A single cored borehole has been drilled into sediments of this unit. Borehole 82/22 ($53^{o}16.967'$N $01^{o}42.323'$E) cored c.6m of Jurassic sediments beneath 44m of Quaternary. Recovery in the borehole was fragmentary. The lithologies encountered range from pale grey, hard sandy limestone to olive-green, muddy siltstones with thin sandstone stringers and lenses. ?Teichichnus burrows commonly occur in the siltstone unit. The basal metre of the core is an olive-grey, calcareous mudstone, with thin buff-coloured limestone nodules or clasts.

Palynological preparations from the sequence yielded good palynomorph assemblages which include the dinoflagellate cysts Nannoceratopsis ambonis Drugg 1978, Nannoceratopsis ambonis and Wallodinium elongatum (Beju 1971)

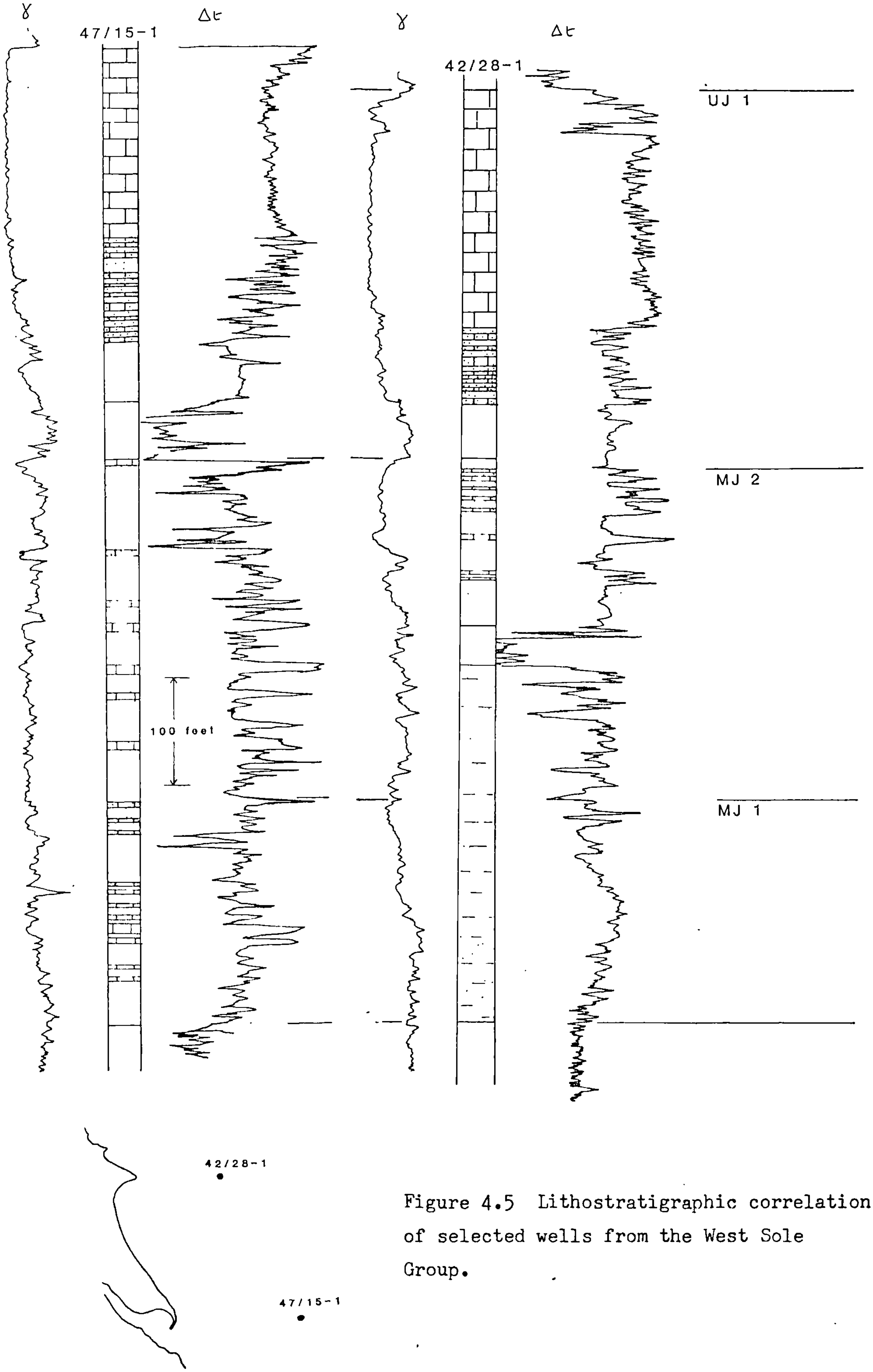


Figure 4.5 Lithostratigraphic correlation of selected wells from the West Sole Group.

Duxbury 1980, together with well-preserved Middle Jurassic spore / pollen flora. These forms suggest an Early Bajocian age for the sequence i.e. equivalent to the Lincolnshire Limestone Formation (J. B. Riding pers comm. 1982).

4.4.2. Unit MJ 2

This unit again shows an upward decrease in the gamma response and increase in sonic velocity , and by comparison with the Nettleton Bottom sequence comprises clays and sands of the Upper Estuarine Series and Blisworth Clay capped by the better cemented units of the Kellaways Beds. This latter unit is traceable eastwards across the Shelf area and into the Sole Pit Trough area (Figure 4.4).

A single cored borehole has been drilled into sediments of unit MJ 2. The borehole 81/48 (53°48.105'N, 01°01.365'E) was sited along the western margin of the Sole Pit Inversion structure. The borehole cored 17.45m of Quaternary sediments before penetrating hard, grey bioclastic limestones (1.55m) overlying greenish-grey, yellow and purple mottled waxy clays (7.06m). These clays pass down gradationally into greenish-grey laminated siltstones and fine grained, carbonaceous sandstones. The basal 0.5m of the sequence comprises interbedded green-grey mudstones and fine, carbonaceous sandstones (Figure 4.10).

The clastic sediments cored in this lower section of the borehole (17.84 - 28.52m T.D.) comprise a fining upward cycle of sedimentation which is closely comparable with sequences described from the Upper Estuarine Series and Blisworth Clay of the East Midlands (Bradshaw and Penney 1981). The upward transition from carbonaceous sands, through laminated siltstones into greenish-grey mottled clays, is typical of the rhythmic, brackish-water cycles of sedimentation which characterises the Bathonian sequence south of the Market Weighton High. In the borehole the cycle is c.8m in thickness with an abrupt erosive base. The lowest 0.5m of sediments probably represent the topmost part of the preceeding cycle. No macrofossils were found in the sequence. Palynological preparations were largely barren, yielding only non-diagnostic miospores and plant debris suggesting a terrestrial or freshwater regime (J. Riding pers comm. 1983).

The top of this clastic cycle is marked by an abrupt change to hard, grey limestone. This thin limestone unit (1.55m) shows a tripartite subdivision into an upper unit of hard crystalline limestone (17.45 -17.84m), a middle unit of soft, grey, silty mudstone (17.84 - 18.27m) and a lower unit of hard, grey, silty limestone (18.27 - 18.96m).

The upper limestone unit contains abundant comminuted shell fragments, including bivalves and echinoderm debris. Bioturbation is evident throughout with subvertical and horizontal burrows. The base of unit is very pyritic and forms a sharp junction with the underlying mudstone. The few identifiable bivalves include *Entolium corneolum* (Young & Bird), *Pseudolimea* cf. *duplicata* (J. de C. Sowerby), ostreid and trigoniid fragments (Dr. Ivimey-Cook pers comm. 1983). The unit yielded an abundant microfauna of foraminifera and ostracoda.

In thin sections the rock is a packstone i.e. grain supported with an interstitial micritic matrix. Angular quartz grains of very fine sand grade occur throughout. Foraminifera are also commonly seen in the sections and the bioclastic debris has frequently undergone recrystallisation to sparry calcite, while retaining its original grain shape.

The middle unit comprises a sequence of grey, silty mudstones with small phosphatised patches or clasts. The mudstone becomes slightly harder and more limy towards the base. Pyritised foraminifera, siderite, quartz grains and carbonaceous debris occur in the unit. A poor macrofauna which included *Pinna* sp., *Plagiostoma* and *Pseudolimea* cf. *duplicata* was recovered from the unit (Dr. Ivimey-Cook pers comm. 1983). Calcareous microfauna were more abundant in this middle unit.

The basal unit comprises a hard, grey, silty bioclastic limestone. Bioturbation is common. The limestone becomes sandy towards the base. Only a few identifiable bivalve fragments were recovered from the unit, these include Entolium?, Meleagrinella?, Pleuromya? and Pseudolimea (Dr. Ivimey-Cook pers comm. 1983). An abundant calcareous microfauna was again obtained from the sequence.

In thin sections this lower limestone unit has more abundant subangular to angular quartz grains than the upper limestone unit. The rock is bioclastic limestone with a packstone texture. Recrystallized sparry, shell and foraminiferal debris is common, set in a sandy, micritic, matrix.

All the taxa identified from the three subdivisions have long ranges in the Jurassic and do not therefore allow precise dating of the sequence. The faunal association and fragmental limestone lithology, overlying sediments of brackish-water 'estuarine' type facies is typical of the Cornbrash. The calcareous microfauna present suggests a Callovian age for the sequence (I. P. Wilkinson pers.comm. 1983).

The sequence described above suggests that during the Bathonian, sediments of brackish-water facies extend eastwards across the East Midlands Shelf into the Sole Pit Trough. It seems likely therefore that much of the expanded West Sole Group succession in the Trough is of Bathonian age. Correlation of the sequence northwards into the Cleveland Basin is limited because only thin Bathonian sediments (?part of the Scalby Formation) are known to occur. Recent palynological work has in fact suggested that much if not all of the Scalby Formation is of Bajocian age and that Bathonian strata were not deposited in the Cleveland Basin (Woollam and Riding 1983). The northern limit of the Bathonian basin of deposition, in the Southern North Sea Basin, probably lay close to the northern edge of the Sole Pit Trough and to the south east of the Scarborough Dome.

4.5. Middle Jurassic sediments in adjacent basins.

4.5.1. West Netherlands Basin (NAM / RGD 1980)

The Middle Jurassic sequences of this basin are preserved only as isolated eroded remnants. They form part of the **Brabant Formation** and consist of a cyclic sequence of sandy limestones, marls and shales deposited in a shallow marine environment, and lie conformably on the Upper Werkendam Shale which ranges up into the Bajocian. Detailed chronostratigraphic subdivision of the sequence has not yet been achieved, but the formation has been divide into several lithostratigraphic units ranging from Bajocian to Oxfordian in age. On lithological grounds it would seem likely that these limestones are possible correlatives of the Lincolnshire Limestone Formation but available data suggests they are Bathonian in age. One of the units, however,the Upper Brabant Limestone, has a high sand content and is of Callovian age and seems a likely equivalent of the Kellaways Beds.

4.5.2. Norwegian - Danish Basin. (Michelson 1978, 1982; Vollset and Doré 1984)

The Middle Jurassic successions of the this basin are primarily deltaic sandstone and shale sequences. A recent revision of the nomenclature of the sequence has introduced a range of local Norwegian terms for the units recognised in the basin (Vollset and Doré 1984). The Middle Jurassic succession now comprises part of the **Vestland Group** formerly the Haldager Formation. The sequence reaches 207m in thickness and comprises a repetitive succession of sandstones , silstones and shales, with abundant carbonized plant remains and thin coals. Five formations have been established within the Group but their exact stratigraphic relationship from area to area are still unclear. Increasingly marine conditions are evident in the sediments from the top of the formation, the Sandnes Formation, which ranges up into the Oxfordian.

4.5.3. Central Graben and Northern North Sea (Deegan and Scull 1975; Brooks and Chesher 1975)

Deltaic sandstones again dominate the Middle Jurassic sequences north of the Mid-North Sea High and comprise the **Brent Unit** and lower part of the **Heather Formation.** The Brent Unit comprises sandstones, conglomeratic in part, with shales and thin coals common. The overlying shales of the Heather Formation (Humber Group) are marine deposits which have yielded ammonites of Middle Bathonian age (Calloman 1979). Rare basaltic lavas and tuffaceous beds, lateral representatives of the volcanic Middle Jurassic Rattray Formation of the Moray Firth area, are interbedded with these clastic sediments in some areas.

4.6. Humber Group- Upper Jurassic

The Upper Jurassic (Oxfordian to Kimmeridgian) succession of the Southern North Sea Basin comprises a series of marine silty shales, sandstones and oolitic limestones which can be closely correlated with the succession at outcrop in eastern England. Subdivision of the sequence on the basis of its downhole log character is very much dependent on the recognition of the marked north to south facies transition that takes place within the Upper Jurassic in both the onshore and offshore areas (Figure 4.6). The Oxfordian succession in particular shows a transition southwards from the Cleveland Basin, where the sequence comprises a thin mudstone unit (Oxford Clay Formation) overlain by moderately thick spicular sandstones and oolitic and bioclastic limestones (Lower Calcareous Grit and Coralline Oolite

Formations), into the East Midlands Shelf area where the Oxfordian is predominantly in a mudstone/siltstone facies (Oxford Clay, West Walton Beds succession) (figure 4.8). In the offshore area the commercial wells drilled document this north to south transition uninterrupted by the effects of the Market Weighton structure. Palaeogeographically the oolitic shoals and banks of the Corallian Formation show a transition south and westwards into slightly deeper-water muddy siltstones of the West Walton Beds (Figure 4.8). The oolite shoals reappear to the south, fringing the London platform e.g. Upware Limestone (Gallois and Cox 1977; Chapter 6).

During the Kimmeridgian this north / south facies transition is no longer apparent though the pattern of sedimentation and subsidence throughout the area still shows quite important subsidence variations with localised thickening of the Kimmeridge Clay (Chapter 6). The facies development is more uniform throughout the basin with typically, organic rich mudstone and cementstone lithologies of the Kimmeridge Clay extending throughout the area (Chapter 6; Cox et al. in prep). The stratigraphy of the Oxfordian - Kimmeridgian sequence is summarised in Figure 4.6.

The Humber Group succession of the offshore area may be divided into two primary units (UJ 1 and UJ 2) which can be traced across the area.

4.6.1. Unit UJ 1

This lower unit, UJ 1, ranges from a sequence of siltstones and interbedded mudstones, which by reference to the Nettleton Bottom and Brown Moor boreholes comprises the Oxford Clay and West Walton Beds (Figures 3.9, 4.4), to the thick sandstones and oolites of the Corallian Formation. Over the East Midlands Shelf the unit shows a spiky high gamma profile decreasing in intensity towards the top of the unit. The sonic profile also shows a spiky profile with interbedded high velocity limestone beds in the West Walton type facies. The log profiles of this unit when traced

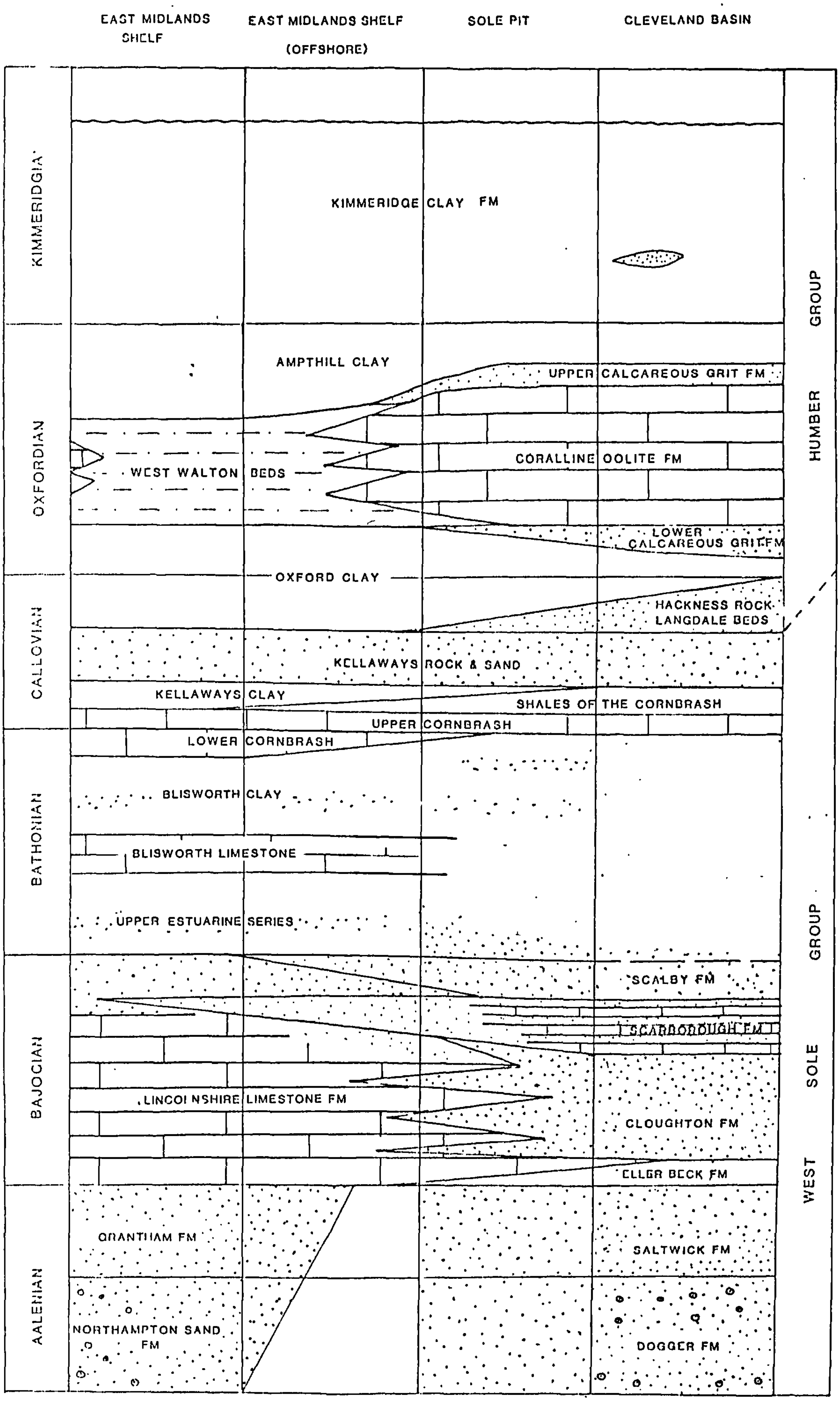


Figure 4.6 Middle and Upper Jurassic stratigraphy of the Southern North Sea Basin.

eastwards suggest that the lower part of the sequence becomes more muddy with fewer limestone interbeds. The top part of the unit, however, shows a high velocity response (Fig 4.4) throughout the Shelf area.

At the eastern margin of the shelf the gradual transition into the spiculitic sands and oolitic limestones of the Corallian Formation occurs. There is consequently a corresponding decrease in the gamma ray amplitude and an increase in the sonic velocity response. It is possible in this area and in the Cleveland Basin to subdivide the sequence into a lower interval, with a spiky gamma / sonic response (Lower Calcareous Grit Formation) and an upper interval of oolitic limestones (Coralline Oolite Formation) with a low gamma / uniformly high velocity profile. A number of shallow boreholes have been drilled over the Coralline Oolite Formation outcrop in the northern part of the basin by the BGS (Enclosure 1), details of the cores are given in Chapter 6. A single commercial core was drilled by British Petroleum in the Corallian Formation outcropping near the West Sole Gasfield (48/6-5; Figure 4.11). The limestone sequence at this site is c.27m thick of which c.8.5m were cored. The limestones are buff to pale grey in colour, hard, oolitic and bioclastic grainstones. The proportion of bioclastic material, which is predominantly highly abraded bivalve debris, is very variable in the core, some of the larger fragments show coarse, sparry recrystallization. Occasional pisolitic layers are present with pisoliths to 3mm. Drusy calcite filled veins and open vugs are a common feature. In the lower part of the core larger bioclastic fragments are less common. On lithological grounds the sequence may be assigned to the Coralline Oolite Formation. The maximum thickness of spiculitic sandstones and oolitic limestones so far proved in the offshore area is c.80m and c.40m respectively (Figure 4.9; 47/9-2, 47/3-2).

4.6.2. Unit UJ 2

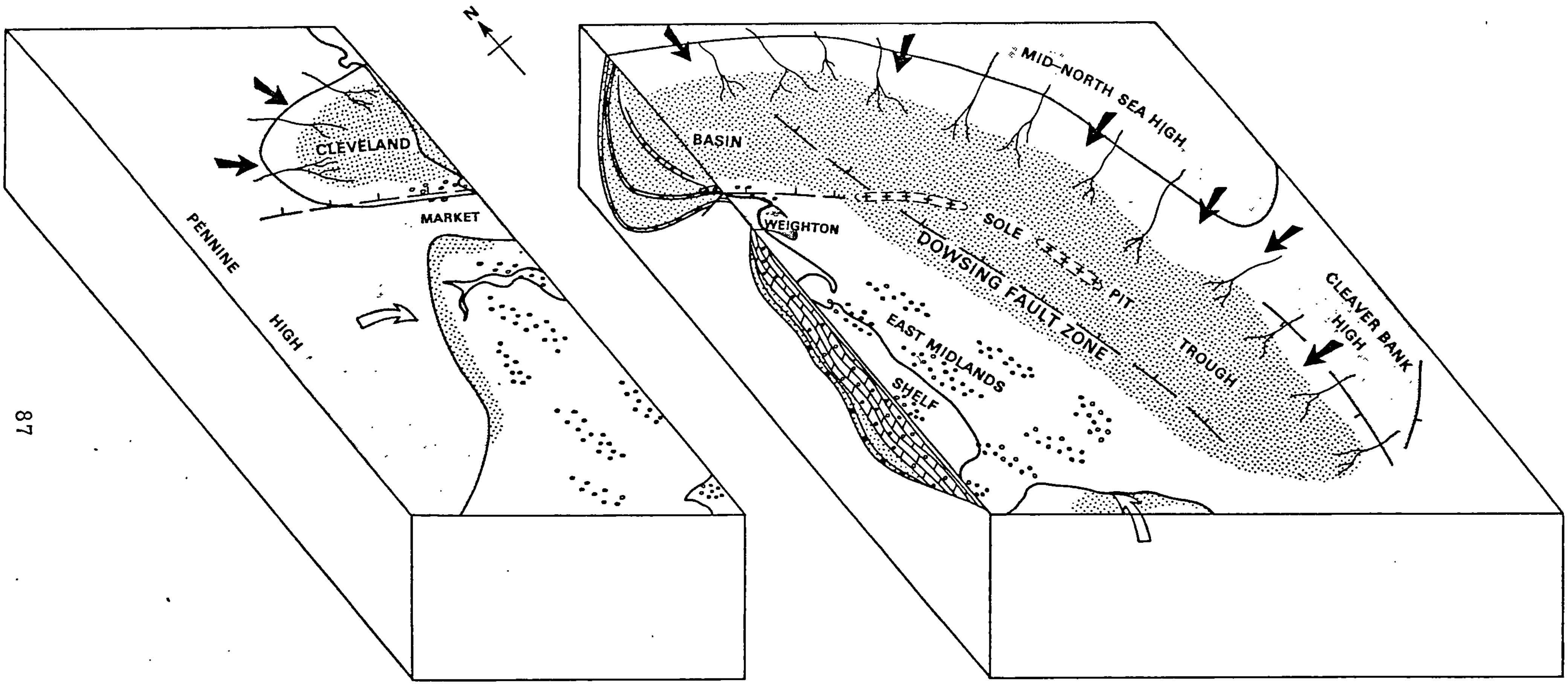


Figure 4.7 Model of the depositional environment of the Lincolnshire Limestone/Cloughton Formation (Bajocian) in the Southern North Sea Basin.

The upper part of this sequence, UJ 2, comprises a series of shales and interbedded limestones which include the Ampthill and Kimmeridge Clays. Typically the sequence shows a comparatively high gamma response with a spiky sonic profile. The boundary between these two clay dominated sequences is not readily identifiable from log responses except in the East Midlands Shelf successions.

Shallow drilling by the BGS suggests that though the Ampthill Clay may be only thinly developed in the offshore area adjacent to the Cleveland Basin, an almost complete Kimmeridge Clay succession is present and shows some evidence of thickening (Chapter 6; Cox et al.in prep)

Locally the effects of salt tectonics considerably disrupt the depositional pattern during the Jurassic. The sequence of wells drilled in quadrant 42 (blocks 28, 29 and 30), for example, in the vicinity of a major salt piercement, show considerable variations in the thickness of their Jurassic successions (Figures 3.2, 3.4). Well 42/28-1 is representative of the thick rim synclinal deposits, whereas well 42/28-2, drilled nearer the crest of the salt structure has a much reduced Jurassic succession. Syndepositional movement of the Zechstein salt may therefore be shown to have exerted considerable influence on not only the thickness of the Jurassic succession in the basin, but also on the facies development.

4.7. Upper Jurassic sediments in adjacent basins.

4.7.1 West Netherlands Basin(NAM / RGD 1980)

Oxfordian oolitic limestones occur in the **Oisterwijk Limestone Member** of the Brabant Formation and may therefore be equivalent, at least in part to the the Corallian Formation of the U.K. sector. During the Kimmeridgian, however, the marine organic rich clays seen in the U.K. area and throughout much of the Northern North Sea in general, are replaced by lignitic sands and clays of the **Delfland Group**; marine clay sequences (**Fourteens Clay**

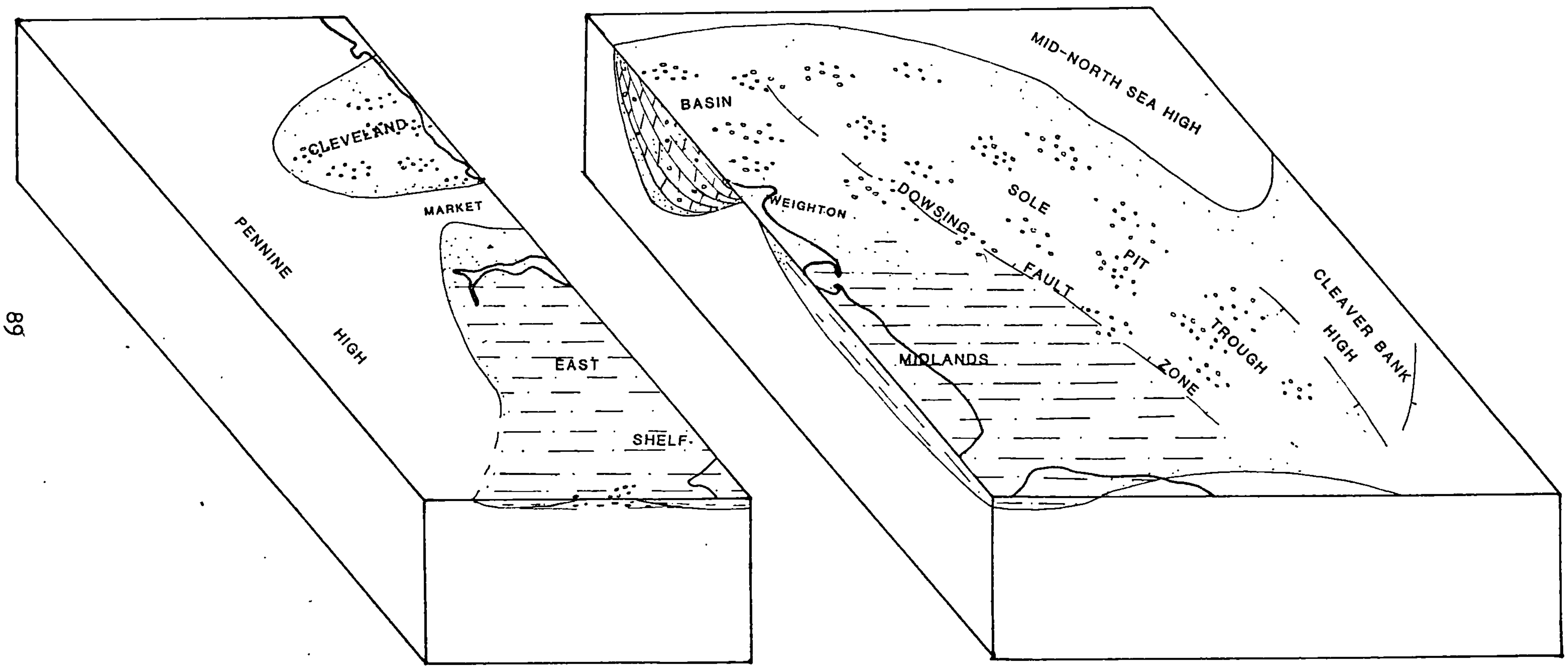


Figure 4.8 Model of the depositional environment of the Corallian Formation (Middle Oxfordian) in the Southern North Sea Basin.

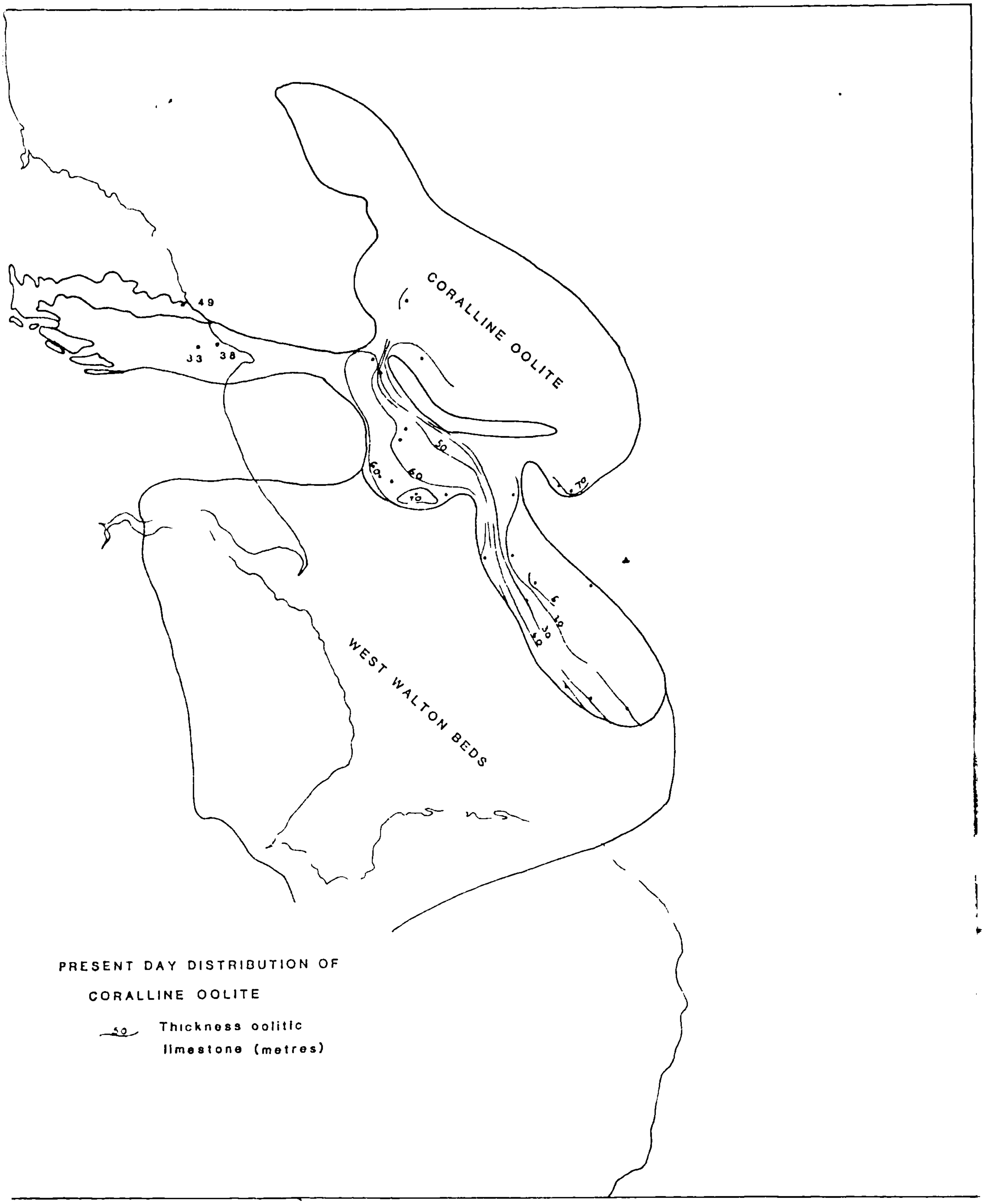


Figure 4.9 Isopachs of the Middle Oxfordian oolitic limestones in the Southern North Sea Basin.

Formation) are noticeably subordinate over the basin.

4.7.2. Norwegian-Danish Basin (Michelson 1978; Vollset and Doré 1984)

The Upper Jurassic successions of this basin are dominated by marine organic-rich mudstone sequences which are believed to be the source rocks for many of the North Sea oilfields. The nomenclature of the succession has recently been comprehensively revised (Vollset and Doré 1984). The sequence was originally referred to the Humber Group, but has now been renamed the **Viking Group**. The former subdivisions of the sequence, the Heather and Kimmeridge Clay formations have been replaced by new local unit names. Three main organic-rich mudstone formations are now recognised, together with a number of more localised marine sand developments. The group includes the very high gamma hot-shale horizons. No oolitic limestone developments have so far been reported from the basin. The interrelationship of many of these new formations in the basin is still very poorly understood.

4.7.2. Central Graben and Northern North Sea (Deegan and Scull 1977)

The Upper Jurassic sequences in the areas north and east of the Mid-North Sea High, in the U.K. sector, comprise the **Heather** and **Kimmeridge** Clay Formations of the Humber Group. They consist predominantly of organic rich marine shales which range from Oxfordian to Portlandian in age. Marked localised facies variations occur, particularly in the Central Graben, with the development of shallow marine sandstones e.g. **Piper** and **Fulmar** Formations along the margins of the grabens, though the exact chronostratigraphic relationship of these sequences has not yet been established.

4.8. Conclusions

The Jurassic succession of the U.K. sector of the Southern North Sea Basin may be divided into a number of lithostratigraphic units which can be

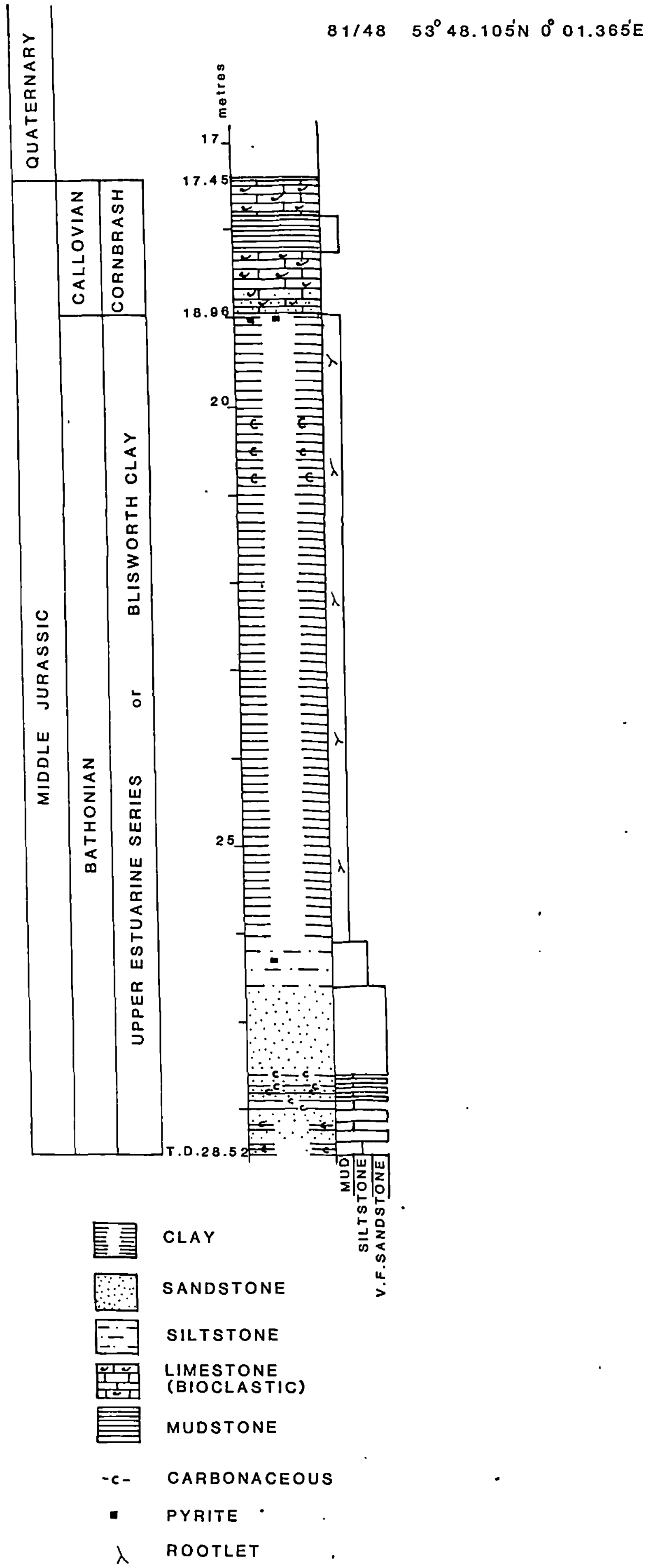


Figure 4.10 Summary Log of the stratigraphy of cored borehole 81/48..

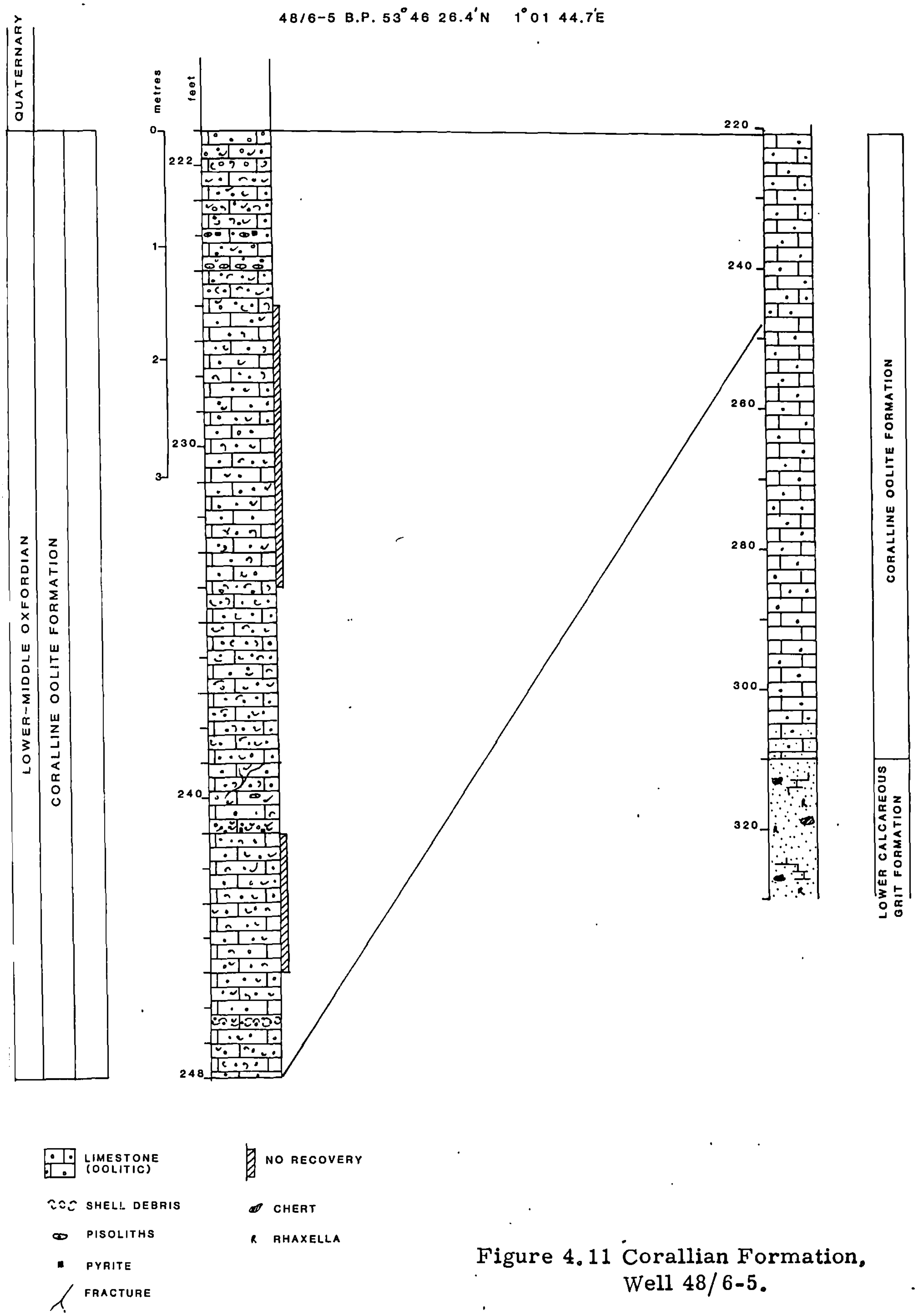


Figure 4.11 Corallian Formation, Well 48/6-5.

correlated throughout the basin. Correlations across the basin are made more difficult by marked north to south facies changes that occurred during the Middle and Upper Jurassic. The constant oscillation of the shoreline across the basin during the Jurassic is probably partly eustatic and partly related to tectonic events in adjacent basins. A major consequence of this is the movement of the facies belts across the basin following the advance and retreat of the shoreline. The main marine transgressions prompted by eustatic sea level rises pushed the shoreline northwards during the Bajocian, while the volcanic updoming of the Central Graben / Viking Graben area was perhaps responsible for the apparent southward retreat of the sea during the Bathonian. By Callovian times the sea reinvaded the northern parts of the Basin and more extensive links with the Central Graben area were probably established by Kimmeridgian times.

CHAPTER 5

Heavy mineral studies of the Middle Jurassic sandstones of Lincolnshire, south Yorkshire and the offshore part of the Southern North Sea Basin.

Heavy mineral studies of the Middle Jurassic sandstones of Lincolnshire, south Yorkshire and the offshore part of the Southern North Sea Basin.

5.1. Introduction

Middle Jurassic (Aalenian to Callovian) sandstone sequences have been drilled in cored boreholes in the Lincolnshire and South Yorkshire areas, Brown Moor (SE 8126 6203), South Cave (SE 9366 3230), Alandale (TA 0007 2584) and Nettleton Bottom (TF 1245 9823) (Gaunt et al. 1980; Bradshaw and Penney 1982). Sandstones from these boreholes have subsequently been subsampled for heavy mineral studies with three main aims: firstly, to determine whether heavy minerals could be usefully used in these sequences to help define the major lithostratigraphic units in a succession where biostratigraphic control is generally poor; secondly, to determine whether further light could be shed on the provenance of the sandstones and thirdly to examine the diagenetic effects, if any, on the heavy mineral assemblages. Previous studies of the heavy minerals from these sequences are limited to work on the Northampton Ironstone (Skerl 1927) and have been complemented only by brief references to heavy mineral distributions e.g. Boswell (1924), Arkell (1933), Smithson (1934, 1941, 1942). No comprehensive systematic description of the heavy mineral assemblages from the sequence has therefore been published, and this paper is an attempt to fill part of this gap in knowledge of the sequence.

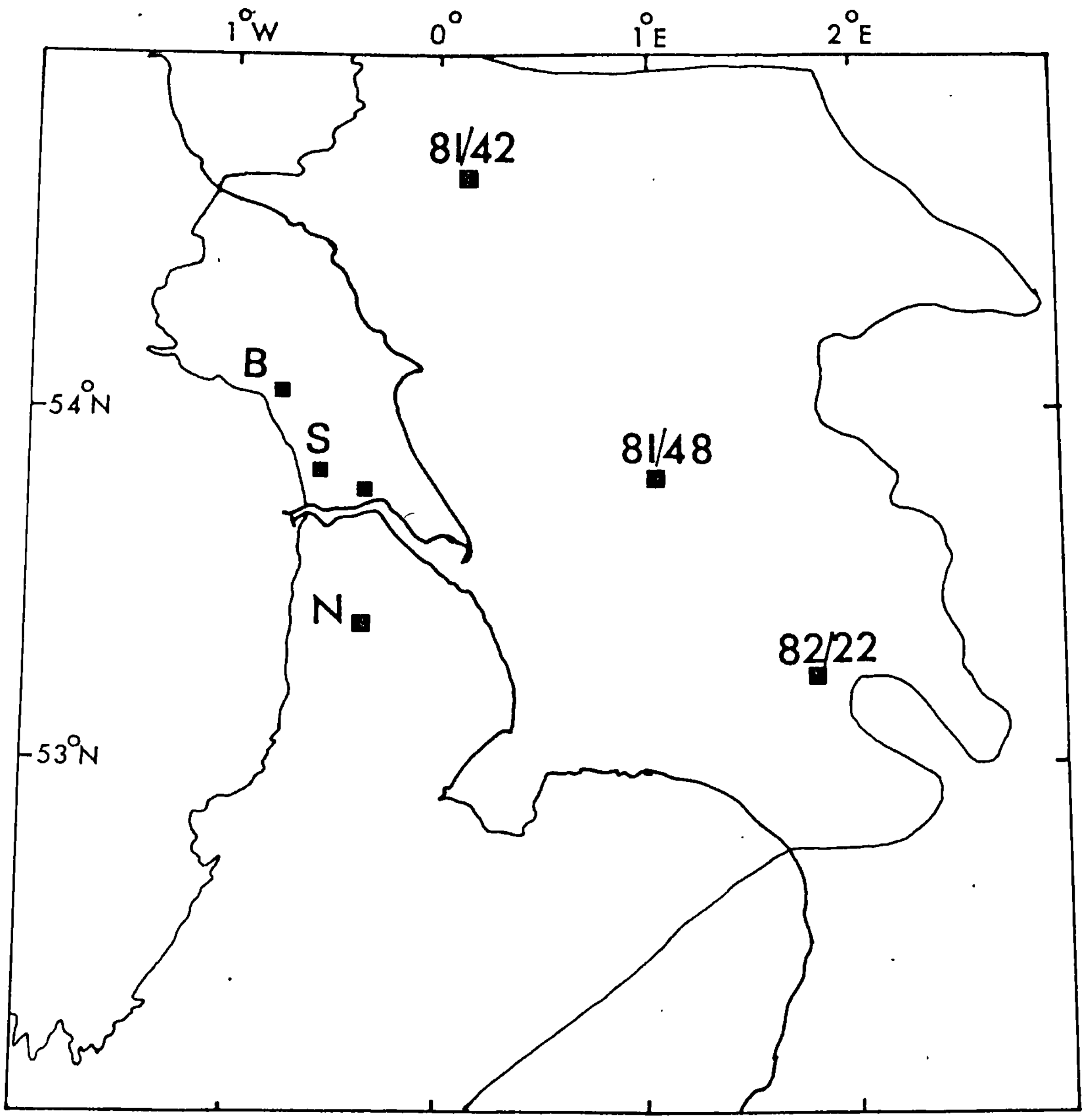
5.2. Stratigraphic summary of the sequence

The Middle Jurassic successions of Lincolnshire and south Yorkshire comprise a sequence up to 80 metres thick, of interbedded shallow marine and non-marine or brackish-water subarkosic and quartzose sandstones (Appendix 2), clays and oolitic or bioclastic limestones. Comprehensive summaries of the succession have been published, notably by Sylvester-Bradley and Ford (1968), Swinnerton and Kent (1976) and Kent (1980b). Subdivision of the sequence is based largely upon lithostratigraphic evidence in the absence of biostratigraphically significant macrofaunas, particularly ammonites, the latter having only rarely been collected from the sequence. Recent work has confirmed earlier suggestions (Bate 1967) of an Aalenian to Bathonian age for the sequence comprising the **Northampton Sand Formation, Grantham Formation, Lincolnshire** Limestone Formation and Upper Estuarine Series / Blisworth Clay (Cope et al. 198 ; Woollam and Riding 1983).

The overlying shallow marine limestones and sandstones of the Upper Cornbrash and Kellaways Beds can however be more reliably assigned to the Callovian on the strength of their still rather impoverished macrofaunal assemblages (Kent 1980b). Only in the vicinity of the Market Weighton High, where littoral sandy sequences predominate and onlap onto the the structure, is the boundary between the Bathonian and Callovian sequences rather more difficult to define. The sandstones are predominantly very fine to fine grained and subarkosic (Appendix 2). The current lithostratigraphic nomenclature for the sequence is shown in Figure 4.6.

5.3. Palaeogeography

The Middle Jurassic sandstones of the Lincolnshire - Yorkshire area were deposited at the western margin of a shallow-water intracratonic basin which extended eastwards across the present North Sea area with probable connections, subsequently severed during the the Late Jurassic / Early Cretaceous erosive phase, into the West Netherlands Basin and Central Graben. During the Bajocian deposition took place in marginal marine or brackish-water environments to the south of the paralic sequences of the Cleveland Basin and north of the main Jurassic sea which covered much of



B BROWN MOOR

S SOUTH CAVE

A ALANDALE

N NETTLETON BOTTOM

82/48 OFFSHORE BOREHOLE SITE

Figure 5.1 Location map of the boreholes.

southern Britain, and whose eustatic sea-level variations caused the regression and transgression of the depositional shoreline across the study area (Hallam 1978). Recent studies of, for example, dinoflagellate cyst assemblages (useful indicators of marine conditions) show that even during periods of non-marine sedimentation marine influences were never long absent from the area (Woollam 1980; Woollam and Riding 1983), particularly over the East Midlands Shelf, reflecting the proximity of the more open marine shelf area to the south-west (Ziegler 1982). During the Bathonian (Upper Estuarine Series / Blisworth Clay) deposition was largely restricted to the area south of the Cleveland Basin, as recent palynological investigations suggest that the whole of the Middle Jurassic of that basin is of Aalenian to Bajocian age (Woollam and Riding 1983).

5.4. Sample Preparation

Approximately 30gms of sample were disaggregated using percussive and ultra-sonic dispersion techniques. The heavy mineral grains were then separated from a single grain-size fraction (63-125 microns) using Bromoform (specific gravity 2.9) following the technique described by Carver (1971). Acids were not used at any stage in the sample preparation. The separations thus obtained included both opaque and non-opaque grains. In the present study only the non-opaque grains are described (Appendix 2).

5.5. Heavy mineral assemblages

The Middle Jurassic sandstones examined yielded non-opaque heavy mineral assemblages of low diversity. Nine heavy mineral species commonly form the major component of these assemblages in preparations from each of the lithostratigraphic units examined (figures 5.3 - 5.7) garnet, zircon, apatite tourmaline, rutile, kyanite, staurolite, sphene, chloritoid. Zircon, tourmaline and rutile are ubiquitous throughout the

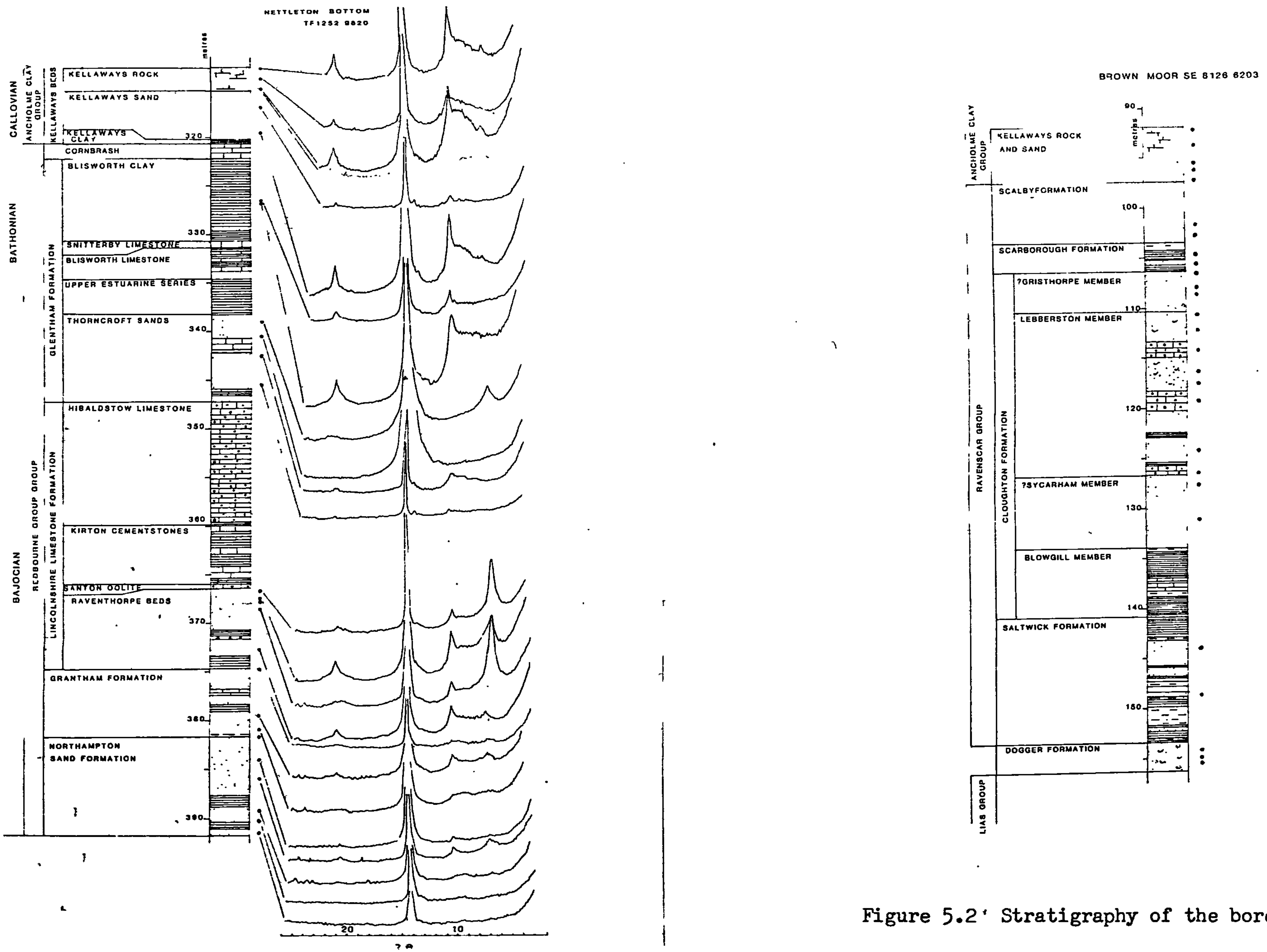


Figure 5.2' Stratigraphy of the boreholes.

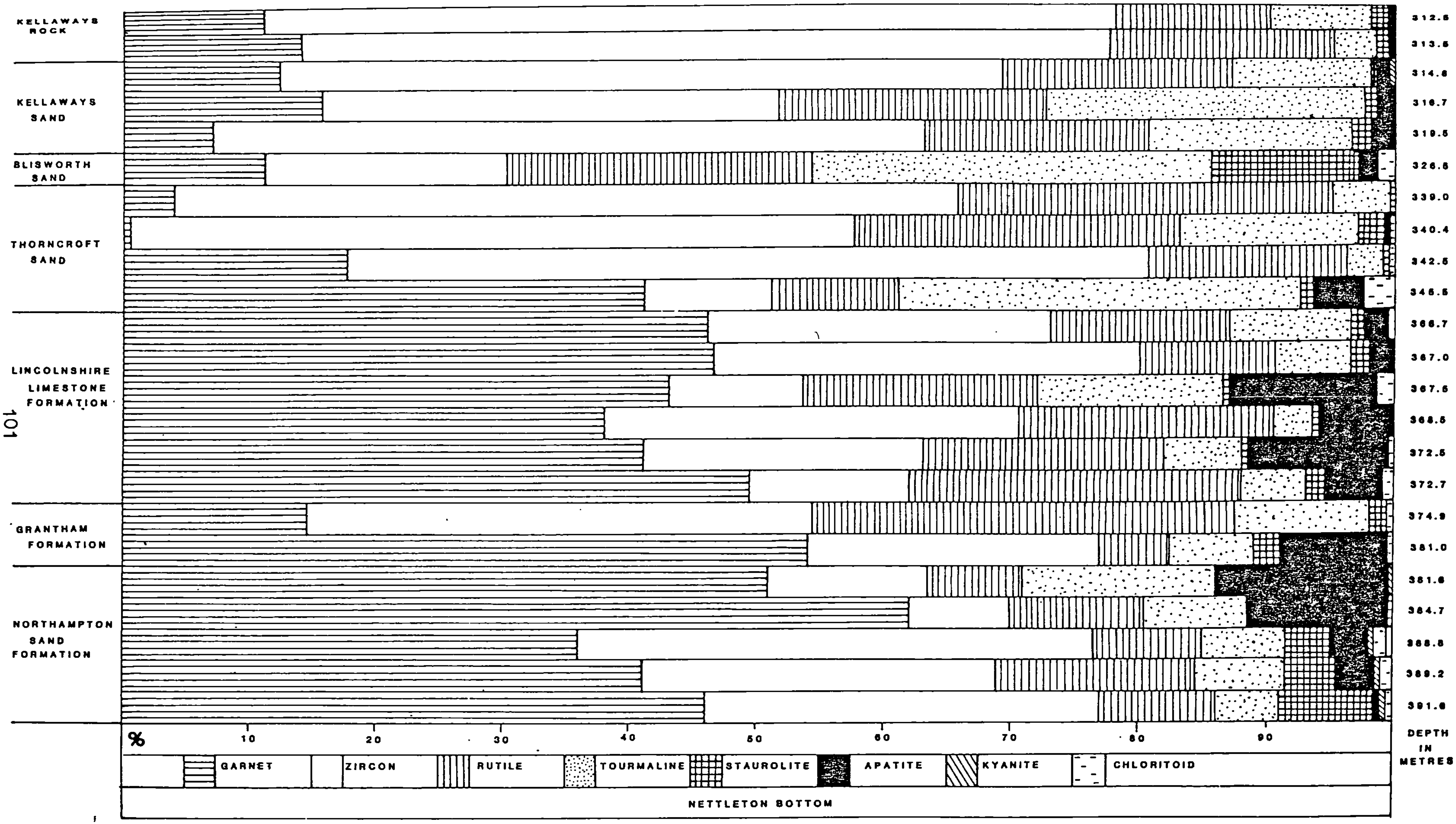


Figure 5.3 Heavy mineral distribution in the Nettleton Bottom borehole (200 grain count, percentage grains).

sequence, while the remaining heavy minerals show some important variations in abundance as discussed below.

A reviw of the stability of heavy minerals in detrital sediments shows in general a number of factors which may influence the final composition of the assemblages, these include:-

1) Provenance - variations in source material.

2) Depositional environment - weathering and early diagenetic changes.

3) Post-depositional changes - deep-burial, late diagenetic effects (intrastratal solution).

In order to assess the relative significance of these factors in the development of the heavy mineral assemblages of the Middle Jurassic sandstones examined in this study, each is discussed below.

5.6. Provenance

Despite the constant eustatic fluctuations in sea level during the Middle Jurassic the bulk of the clastic sediment supplied to the Southern North Sea Basin is considered to be of local derivation with only a minor component from more distant sources. The Pennine High in particular, which is composed of Carboniferous, Permian and Triassic sediments, has yielded heavy mineral assemblages similar to those found in the Middle Jurassic assemblages examined in this study (Table 5.1). Of the minerals found in the Middle Jurassic assemblages from the study area only chloritoid (itself extremely rare in the assemblages), kyanite and staurolite are unlikely to have been derived from local sources. Kyanite, which is most abundant in the south Yorkshire sequences at Brown Moor, Alandale and South Cave, has rarely if ever been described from the pre-Jurassic sequences of the area. Staurolite grains, despite their apparent abundance in some local Palaeozoic and Triassic sediments (Burton 1923, Smithson 1931) usually occurs in those sediments as ragged etched forms (Smithson op cit.). Such a

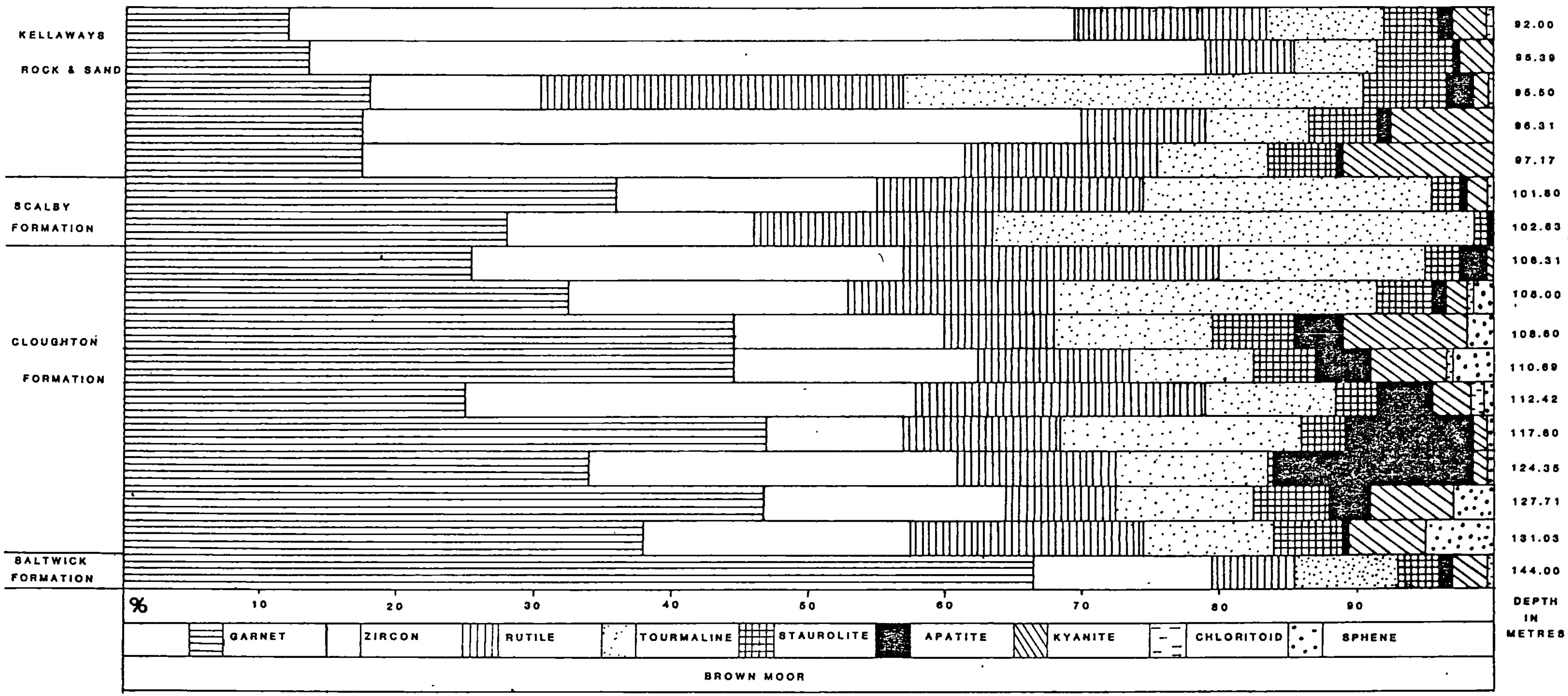


Figure 5.4 Heavy mineral distribution in the Brown Moor borehole
(200 grain count, percentage grains)

grain morphology is unlikely to have withstood reworking and abrasion during transport. It therefore seems probable that the staurolite grains of the Middle Jurassic sequences have a more distant provenance and have suffered post-depositional modification (see section 5.8).

During the Middle Jurassic regional palaeogeographic considerations suggest that source areas which could supply staurolite, kyanite and chloritoid to the basin were limited to the regionally metamorphosed terrains of the Scottish Highland Massif to the north or the Armorican Massif to the south. The distribution of kyanite is particularly interesting as regards the relative importance of these two areas in deciding the provenance of the Jurassic sands.

In a detailed study of the kyanite-bearing sands of the Late Toarcian in south-west Britain, a southerly source in the Armorican Massif was favoured for the derivation of the kyanite (Boswell 1924). However, in a more recent study of the late Toarcian sands from a deep borehole in Dorset, Morton (1982) suggested that a northern derivation from the Scottish area was equally as likely. A southern source area, was also suggested for the the kyanite in the Northampton Sandstone of Aalenian age (Skerl 1927), while the abundance of kyanite in the Middle Jurassic sandstones south of the Market Weighton High and its apparent rarity in the Cleveland Basin led Smithson (1931, 1942) also to favour a southern provenance for kyanite.

In the present study area the Middle Jurassic sandstones at Brown Moor, South Cave and Alandale contained abundant kyanite while at Nettleton Bottom kyanite was rare or absent throughout the sequence, kyanite then becomes abundant again further southwards in the Northampton area (Skerl 1927). The inference here is that either kyanite did not reach the Nettleton area from a southern or northern source or, if originally present, has been removed diagenetically at some later stage. The removal of kyanite by diagenetic changes has obvious implications when considering the provenance of the Middle Jurassic sandstones of south Yorkshire and Lincolnshire. In the Cleveland Basin the absence of kyanite from the sediments of the axial areas of the basin was attributed to late stage diagenetic effects resulting from deep burial of the sequence (Smithson 1941; Figure 5.7). The susceptibility of kyanite to dissolution during deep burial has also been confirmed in many subsequent studies e.g. Morton 1979a, 1979b, 1982, 1984. Though the absence of kyanite in the Lincolnshire basin i.e. Nettleton borehole is not attributable to deep burial effects (see section 5.8) I believe that kyanite was probably present in the original sediments across the whole area. Effective transport paths for the the sediment into the Yorkshire-Lincolnshire area, either along the eastern margin of a Pennine-Scottish Massif or via the Central Graben (Eynon 1981, Leeder 1983), if it is assumed that the Mid-North Sea High was an active barrier to more direct sediment influx from the north, appears to me to be more likely than derivation by longshore drift of sands from Armorica, skirting the western margin of the main Jurassic shelf sea area which covered much of southern Britain at this time.

No comprehensive studies of the heavy minerals from the Middle Jurassic outcrops of north-east Scotland or in the adjacent offshore basins have yet been published to confirm or deny a northern source for the more exotic heavy minerals of the Lincolnshire-Yorkshire successions. A limited number of samples from the Brora area in north east Scotland did not yield any particularly significant minerals which might allow comparisons to be made (Hudson 1964). However, a recent study of the Middle Jurassic sandstones (Brent Group) in the Viking Graben yielded heavy mineral assemblages of considerably greater variety (Morton and Humphries 1983). These sediments, which in addition to the minerals recognised in the Lincolnshire-Yorkshire area, also contain small proportions of epidote, clinopyroxene, horn blende, clinozoisite and sillimanite were considered to have been sourced from the Orkney / Shetland platform. In the Danish Sub-Basin similarly diverse assemblages were considered to have been derived from the Fenno-Scandian Shield (Larsen 1966). This contrast between the more varied assemblages in the Middle Jurassic sediments north of the Mid-North Sea - Rinkobing-Fyn High and those to the south presumably reflects the more direct derivation of the former from freshly eroded regionally metamorphosed terrains, rather than the latters derivation by erosion of pre-existing sediments.

A limited number of samples have so far been examined from Middle Jurassic cored boreholes in the offshore southern North Sea area, boreholes 81/42 (54°39.106'N 0°06.827'E), 81/48 (53°48.105'N 1°01.365'E) and 82/22 (53°16.967'N 1°42.323'E) (Figure 5.1). Geophysical log correlations show that the Jurassic lithostratigraphic units of the East MIdlands extend offshore as far eastwards as the Dowsing Fault complex beyond this fault complex the succession thickens considerably into the Sole Pit Trough (Chapter 4). Preparations from sequences at the margin of this Trough yielded heavy mineral assemblages similar to those of their lithostratigraphic equivalents onshore (Figure 5.6). Particularly notable however in borehole 82/22 (Lincolnshire Limestone Formation - J. Riding personal communication) which is sited close to the axis of the trough, is the abundance of comparatively fresh garnet grains in the assemblages precluding any deep burial of the sediments as is thought to have occurred in the Cleveland Basin.

5.7. Environment of deposition: early diagenesis, weathering.

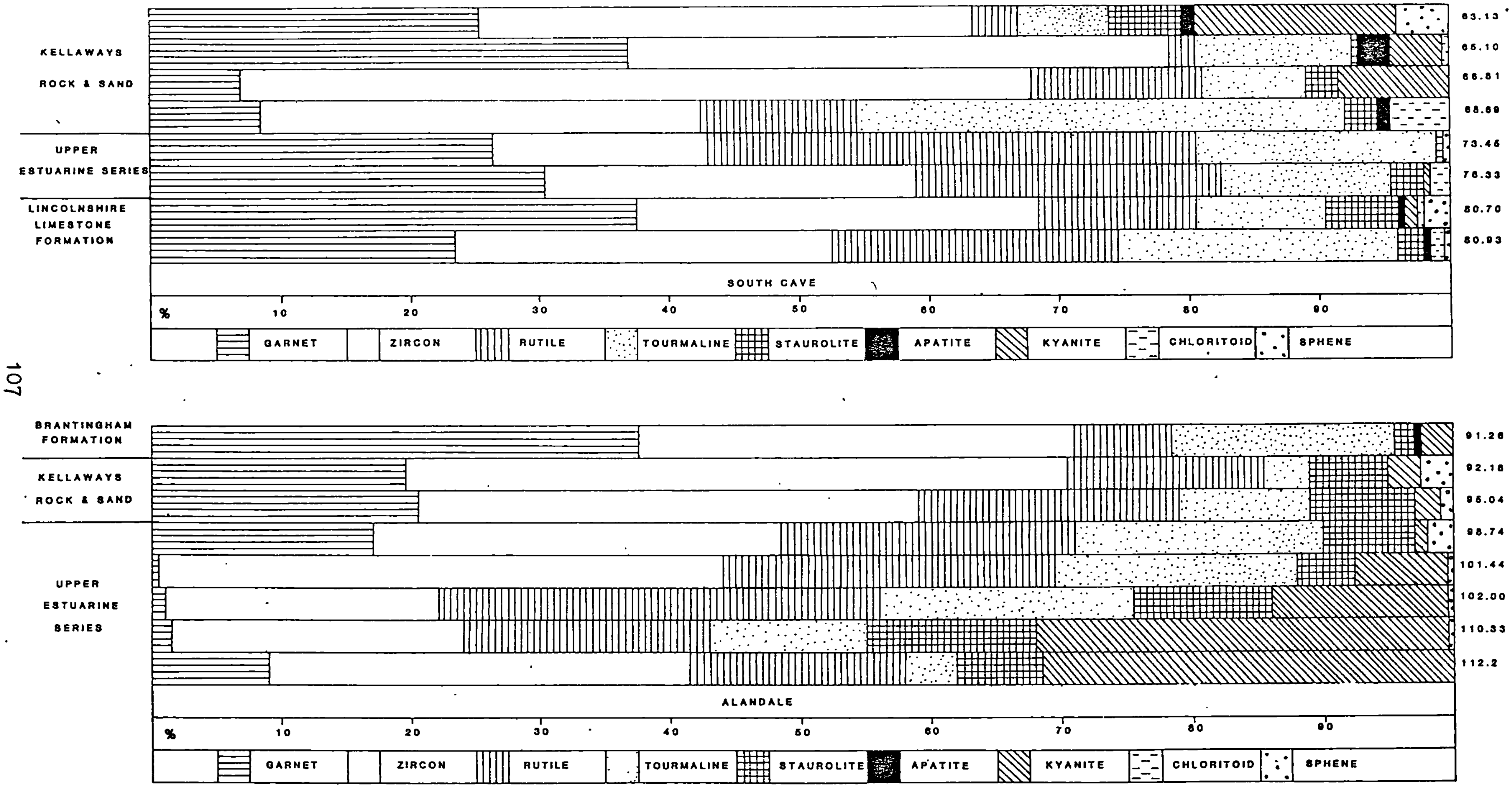


Figure 5.5 Heavy mineral distribution in the South Cave and Alandale boreholes (200 grain count, percentage grains).

Among the minerals present in the heavy mineral assemblages from the Middle Jurassic sandstones, probably the most susceptible to weathering and diagenetic changes during the early depositional history of the sediment is the mineral apatite. Apatite is particularly vulnerable to dissolution under acidic conditions of deposition. Such conditions are most likely to develop in the non-marine or brackish water phases of sedimentation in the basin. Under deep burial conditions apatite in general becomes more stable as conditions become increasingly alkaline. In the sample preparations from this study (which were not treated with acid during disaggregation) apatite was found to be particularly abundant in the marine sands within the Lincolnshire Limestone Formation and its northern equivalent the Cloughton Formation (Lebberston Member) (Figure 4.7) (Gaunt et al. 1980). In the non-marine sequences, apatite is notably less abundant both in the Brown Moor and Nettleton Bottom sequences (Figure 5.3, 5.4).

Euhedral apatite grains were noted in a number of assemblages from the marine sediments of the Kellaways Rock and Sands, contrasting strongly with its more normal abraded egg-shaped form. Such grains are usually considered to be of possible volcanic origin.

5.8. Post-depositional changes (late diagenetic effects).

Late diagenetic effects (i.e. intrastratal solution) on heavy mineral assemblages, have been widely documented (see for example Smithson 1942; Grimm 1973; Morton 1984). The Middle Jurassic assemblages of this study show a preponderance of the more stable heavy mineral grains, but post-depositional modification of some grains can be demonstrated. The most obvious post-depositional effects include grain-pitting, the development of etched and mammillated surfaces and grain facetting. The minerals predominantly showing these effects are garnet, staurolite and kyanite. Grain etching or intrastratal solution is attributed to the effects of hot,

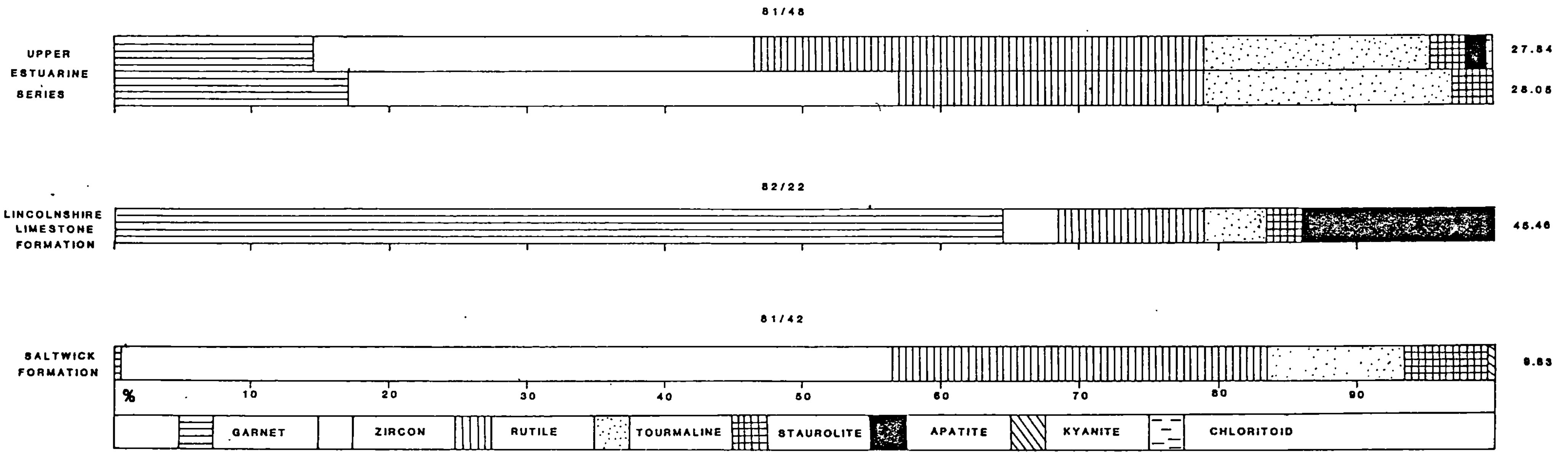


Figure 5.6 Heavy mineral distribution in offshore boreholes 81/42, 81/48 and 81/22 (200 grain count, percentage grains).

highly acidic, corrosive fluids moving freely through the pore spaces of the sediments. Burial of the sediment, by raising both the pressure and temperature of the fluids, enhances the corrosive potential of such fluids.

The garnet grains are generally fresh to moderately etched in all the assemblages examined. Grain pitting, resulting from the preferential etching of inclusions to give a 'swiss cheese' - like appearance to the grains, commonly occurs and the development of mammillated surfaces is extremely common. More severely etched forms , producing rather irregular grains were rarely noted but the more extreme conditions of etching to produce skeletal forms (e.g. Smithson 1942) were not observed in any of the assemblages. The garnet grains suggest a fairly simple burial history for the sediment as would be expected on the comparatively stable East Midland Shelf and around the Market Weighton High. It is of interest to note that Morton (1984) recorded the development of mammillated etch features at shallow depths in the early Tertiary sediments if the Central Graben while more severely etched forms were not encountered until depths of over 2000m were reached.

Staurolite grains range from full prismatic forms to "concertina-like", vestigial saw-toothed grains (Plate 5.1). This saw-toothed etching is particularly prominent in the Brown Moor and Nettleton assemblages and is less apparent in the South Cave and Alandale sequences which lie closer to the Market Weighton structure. The kyanite grains present also range from prismatic and tabular grains to severely etched forms with pointed terminations and serrations (Plate 5.2).

The susceptibility of these three minerals to intrastratal solution during deep burial has been demonstrated in the Cleveland Basin (Smithson 1941) and more recently in the Central Graben by Morton (1984). In the Middle Jurassic sediments of the Cleveland Basin the heavy mineral assemblages become increasingly depleted in kyanite, staurolite and garnet as the axis of the Basin is approached. Along the axis of the Basin which is assumed to coincide with the greatest depth of burial of the sequence (c.2500m - according to Hemingway and Riddler (1983)) the assemblages show a complete absence of kyanite, staurolite and garnet. (Smithson 1941; see Figure 5.7). A similar pattern emerges in the Central Graben where the assemblages become increasingly depleted in kyanite, staurolite and garnet in the more deeply buried sediments (c.1800m+) along the Graben axis (Morton 1984).

The comparatively stable burial history of the East Midlands Shelf area, however, precludes any deep burial control on the etching of the kyanite and staurolite. It is necessary therefore to postulate an alternative mechanism to account for the etching particularly of the kyanite and staurolite grains and to a lesser extent the garnet grains in the East Midlands area. One such mechanism, which may have acted to enhance the corrosive potential of the pore fluids, may have been the flushing of the sequence by fluids expelled from more deeply buried sediments. The inversion of the adjacent Sole Pit and Cleveland Basin structures may have provided one such source of fluids; another may have been the thick Carboniferous - Triassic sediments which underlie much of the area. It is also perhaps worthy of note that recent geophysical studies have postulated the existence of two granitic masses beneath the Market Weighton - East Midlands area and as a consequence geothermal heat flow gradients in the area are at present somewhat higher than might otherwise be expected and may possibly have been of even greater significance in the past.

5.9. Conclusions

The heavy mineral assemblages from the Middle Jurassic sandstones of LIncolnshire and south Yorkshire have proved to be of limited value for

Plate 5.1 Scanning Electron Micrographs of selected heavy mineral grains showing leaching effects of intrastratal solution.

a) Kyanite grain, Kellaways Sand, Brown Moor borehole.

b) Kyanite grain, Kellaways Sand, Brown Moor borehole.

c) Kyanite grain, Kellaways Sand, Brown Moor borehole.

d) Staurolite grain, Kellaways Sand, Alandale borehole.

e) Kyanite grain, Cloughton Formation 112.0m, Brown Moor borehole.

f) Kyanite grain, Cloughton Formation 112.0m, Brown Moor.

Plate 5.2 Photomicrographs of heavy mineral grains (63-125 microns) showing leaching effects of intrastratal solution.

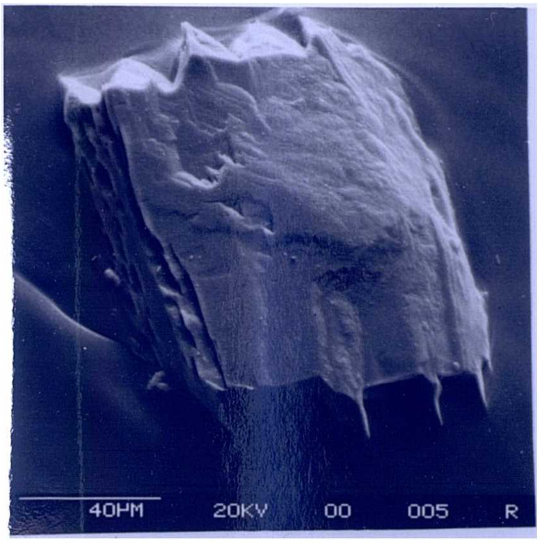
a) Kyanite grain, Kellaways Rock 95.39m, Brown Moor borehole.

b) Kyanite grain, Kellaways Sand 96.31m, Brown Moor borehole.

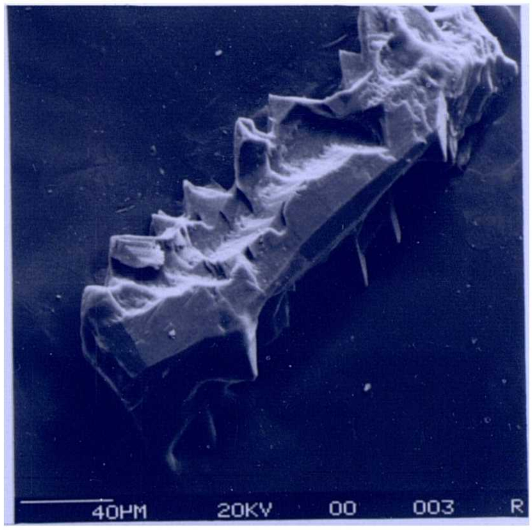
c) Kyanite grain, Kellaways Sand 96.31m, Brown Moor borehole.

d) Kyanite grain, Kellaways Sand 96.31, Brown Moor borehole.

e) Staurolite grain, Kellaways Sand 316.7m, Nettleton Bottom borehole.


40PM 20KV 00 005 R

a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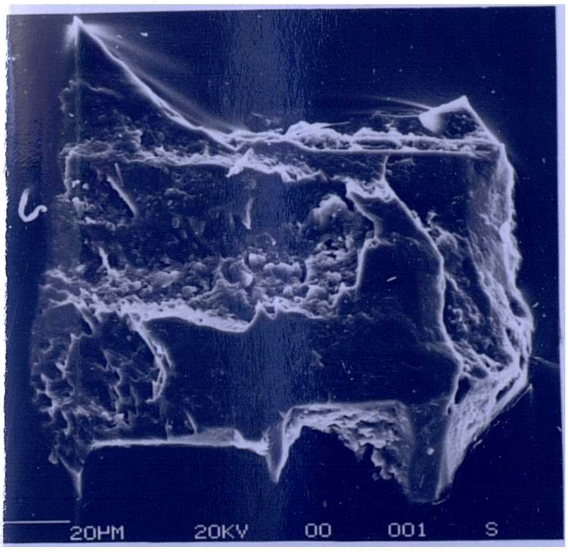
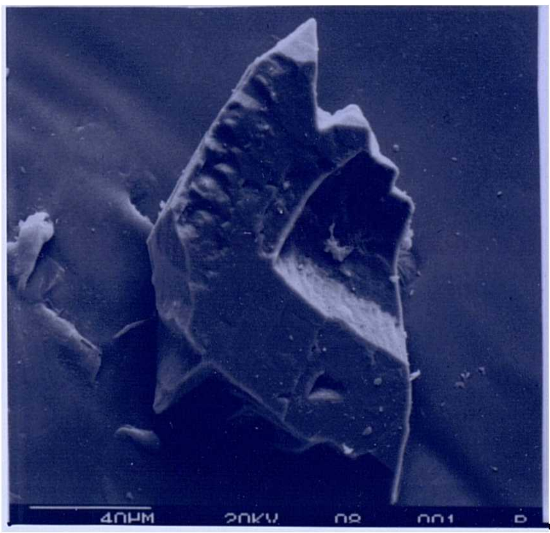
b


20PM 20KV 00 001 S

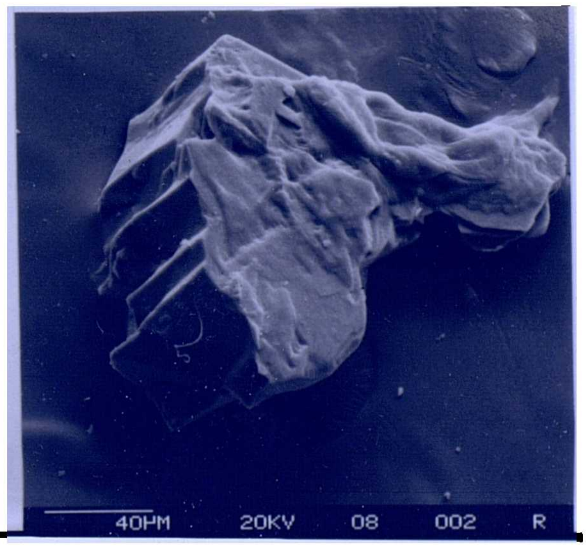
c


40PM 20KV 04 001 R

d



e


40PM 20KV 08 002 R

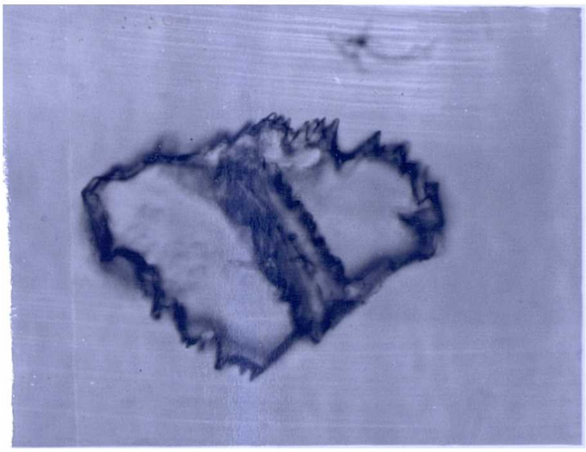
f

stratigraphic correlation. A correlation between assemblages from the principal marine units across the area, based particularly on the abundance of apatite in those units may be made, but the predominantly local provenance for much of the clastic sediment throughout the Middle Jurassic precludes any real variations either stratigraphically, between different units, or laterally throughout individual units.

Despite, however, the comparative maturity of the assemblages seen throughout the succession there are a number of interesting features worthy of comment. As already mentioned the bulk of the sediment including the heavy minerals is of local derivation largely from the Pennine-Mid North Sea High and possibly from the Anglo-Brabant High. There is, however, a small but important exotic content to the assemblages which includes primarily kyanite, staurolite and chloritoid which have a more distant source probably in the regionally metamorphosed sediments of the Scottish Massif.

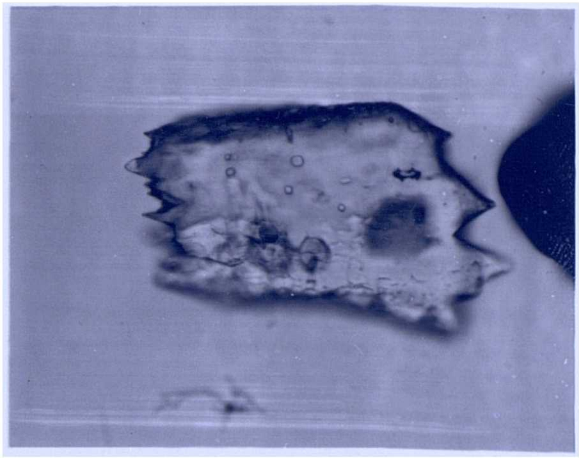
A second feature of note is the moderately severe etching primarily exhibited by the kyanite and staurolite grains. Normally this type of etching is ascribed to intrastratal solution during deep burial of the host sediments, in this case however regional considerations , as discussed earlier point to a relatively shallow burial history for the area and the grain etching has here been attributed to flushing of the sediment pile by hot, highly acidic fluids expelled from more deeply buried sediments either of the same age or as seems more likely from an older sediment pile.

Thirdly, the presence within the assemblages from the Kellaways beds in both Lincolnshire and South Yorkshire of euhedral apatite grains is worthy of note. These grains are considered to represent residual grains of volcanic origin. Euhedral apatites of volcanic origin have been described, for example, from the Callovian sediments in the Isle of Skye (Knox 1977).



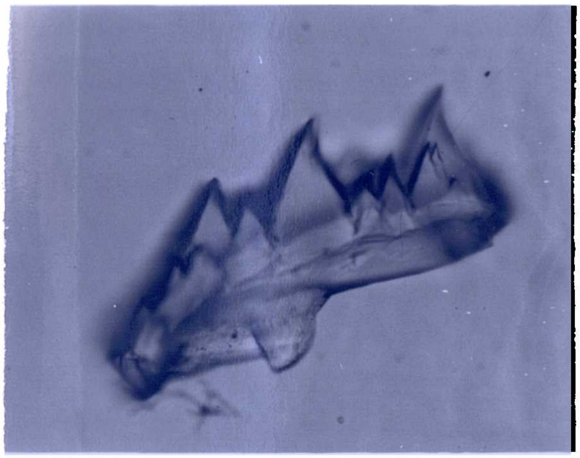
60µm

a



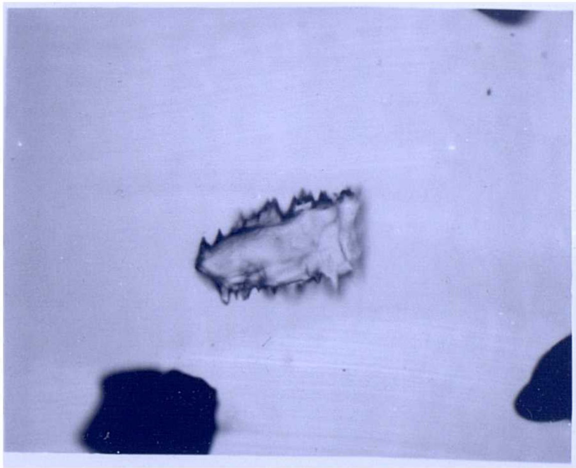
80µm

b



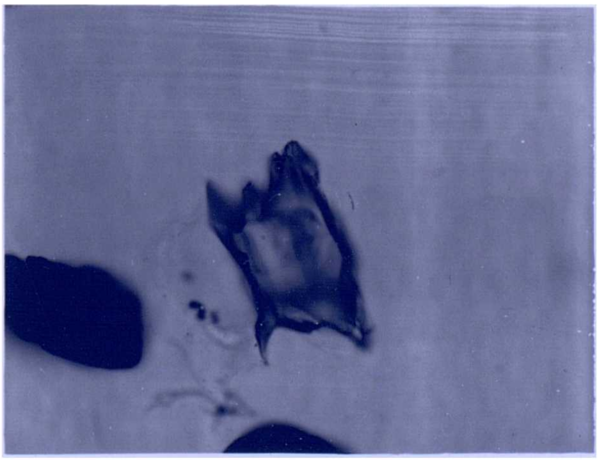
60µm

c



40µm

d



40µm

e

Callovian volcanism is not well documented in the European area. However, given the as yet, the poor biostratigraphic control on, for example, the thick volcanic sequences of the Central Graben area, a volcanic source for the euhedral apatites must remain problematical for the moment.

Finally one further point concerning the Jurassic heavy mineral assemblages of eastern England is worthy of comment. Two cored boreholes from the axial area of the Cleveland Basin at Scarborough, the Castle Head (TA 0506 8948) and Scalby Ness (TA 0363 9108) boreholes, have subsequently been examined for comparison with the East Midlands area (Figure 5.7). The heavy minerals present in these Bajocian and Callovian sequences compare closely with those described by Smithson (1944) from the basin. The absence or low proportions of garnet and apatite are notable features of the Bajocian assemblages while in the Callovian sediments garnet proportions are significantly increased. The absence of garnet in the Bajocian sediments has usually been attributed to deep burial, this raises the question why the garnet proportions should increase in the Callovian interval if the whole of the Jurassic sequence has undergone a similar deep burial history. It seems improbable that this deep burial occured in pre-Callovian times i.e. during the Bathonian. Perhaps an alternative answer may be that the loss of garnet may be merely a feature of prolonged flushing of the sediment pile during the Bathonian hiatus and that deep burial is not necessarily to explain the heavy mineral depletion. The axial area which is the most depleted in terms of the heavy minerals, being the thickest and therefore deepest part of the sediment pile, was most accessible to hot fluids originating from deeper in the basin, whose movement was perhaps triggered by inversion of the basin beginning possibly as early as the Bathonian.

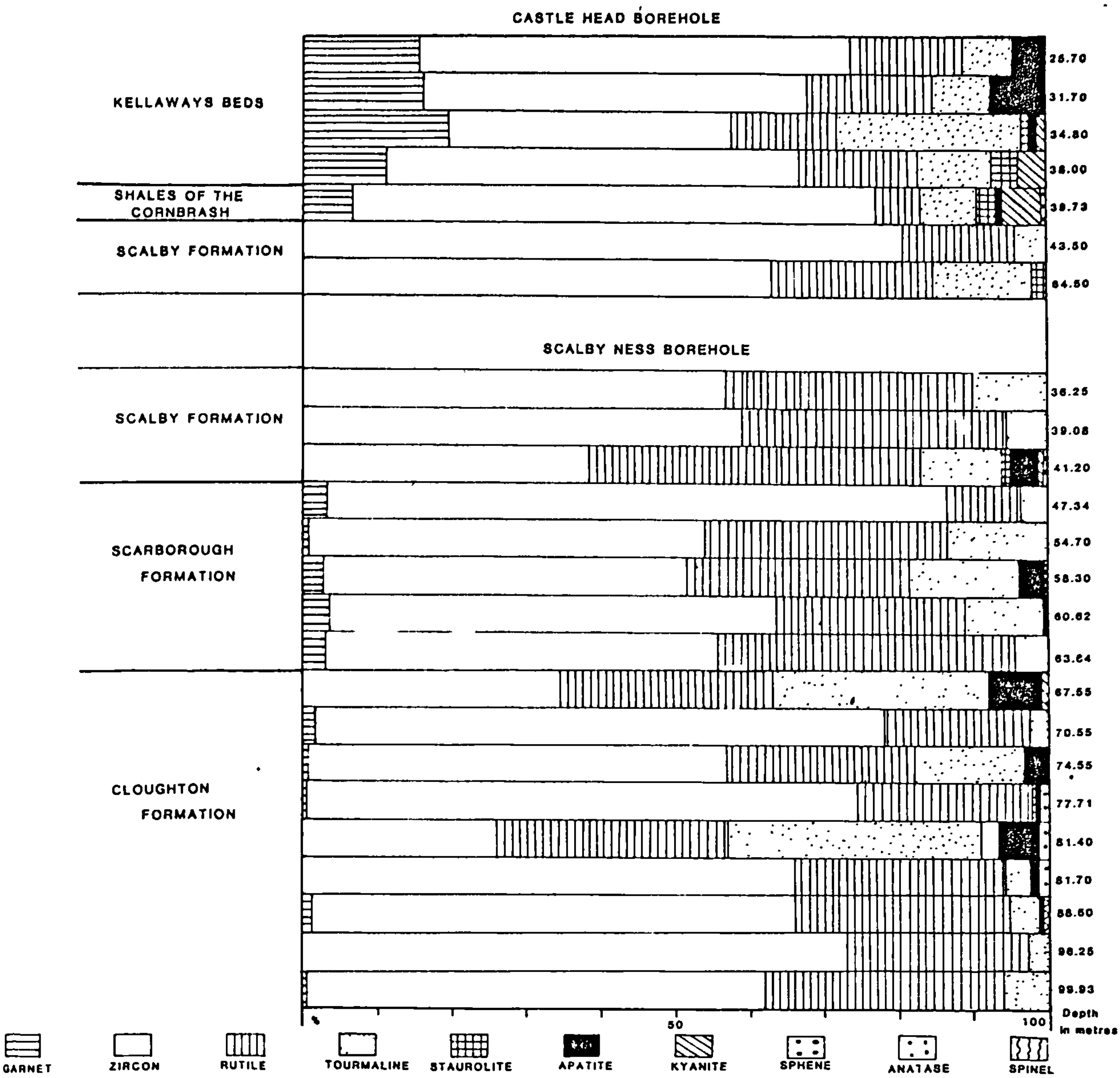


Figure 5.7 Heavy mineral distribution in the Castle Head and Scalby Ness boreholes of the Cleveland Basin.

TABLE 5.1

Lott (this study)	Harrison 1971	Crampton 1958	Burton 1923	Smithson 1931
JURASSIC	MILLSTONE GRIT	MAGNESIAN LST.	BUNTER	TRIASSIC
Zircon	Zircon	Zircon	Zircon	Zircon
Tourmaline	Tourmaline	Tourmaline	Tourmaline	Tourmaline
Rutile	Rutile	Rutile	Rutile	Rutile
Garnet	Garnet	Garnet	Garnet	Garnet
Apatite	Apatite	Apatite	Apatite	Apatite
Staurolite	Staurolite	Staurolite	Staurolite	Staurolite
Kyanite			Kyanite	
Chloritoid				
Sphene		Sphene		

%

		GARNET	ZIRCON	STAUROLITE	CHLORITOID	KYANITE	APATITE	RUTILE	TOURMALINE	PLEONASTE
Kellaways Rock	312.5	11	67	1.5	0	0	0.5	12	8	0.5
	313.5	14	63.5	1	0	0	0.5	17.5	3.5	
Kellaways Sand	314.8	12	57	0.5	0	0.5	1	18	11	
	316.7	15.5	36	1	P	0	1.5	21	25	
	319.5	7	56	1.5	0	0	2	17.5	16	
Blisworth 'Sand'	326.5	11	19	11.5	1.5	0	1.5	24	31.5	
	326.7									
Thorncroft Sand	339	4	61.5	0.5	0	0	0	29.5	4.5	
	340.4	0.5	57	2	0.5	0	0.5	25.5	14	
	342.5	17.5	63	0.5	0.5	0	0	15.5	3	
	345.5	41	10	1	2.5	0	4	10	31.5	
Lincolnshire Limestone	366.7	46	27	1	0	0	2	14	9.5	0.5
	367	46.5	33.5	1.5	0	0	2	10.5	6	
	367.5	43	10.5	0.5	1.5	0	11.5	18.5	14.5	
	368.5	38	32.5	0.5	0	0.5	5.5	20	3	
	372.5	41	22	0.5	0.5	0	11	19	6	
	372.7	48.5	13.5	1.5	1	0	4.5	26	5	
Grantham Formation	374.9	14.5	40	1	0.5	0	0	33	10.5	0.5
	376									
	381	54	23	2	0.5	0	8.5	5.5	6.5	
Northampton Sand	381.6	51	12.5	0	0	0.5	13.5	7.5	15	
	384.7	62	8	0	0.5	0	11	10.5	8	
	388.8	36	40.5	3.5	1	0.5	3	8.5	6.5	0.5
	389.2	41	28	4	1	0.5	3	15	7.5	
	390.1									
	391.6	46	31	7.5	0.5	0.5	0.5	9	5	

NETTLETON BOTTOM
TABLE 5.2

%

		GARNET	ZIRCON	STAUROLITE	CHLORITOID	KYANITE	APATITE	RUTILE	TOURMALINE	SPHENE
	92.00	12	57.5	4	0.5	2.5	1	15	7.5	
Kellaways Rock and Sand	95.39	13.5	65.5	5.5	0	2.5	0.5	6.5	6.0	
	95.50	18	12.5	6	0.5	1.0	2.0	26.5	33.5	
	96.31	17.5	52.5	5	0	7.5	1	9	7.5	
	97.17	17.5	44	5	0	11	0.5	14	8	
Sealby Formation	101.80	36	19	2	0.5	1.5	0.5	19	21.5	
	102.63	28	18	1	0	0	0.5	17.5	35	
Scarborough Formation	104.80									
	105.69									
	106.31	25.5	31.5	2.5	P	0.5	2	23	15	
	108.00	32.5	20.5	4	0.5	1.5	1	15	23.5	1.5
	108.60	44.5	15.5	6	0	9	3.5	8	11.5	2
	110.[illegible]	44.5	18	4.5	0.5	5.5	4	11	9	3
Cloughton Formation	112.42	25	33	3	1	2.5	4	21	9.5	1
	116.50									
	117.60	47	10	3	0	1	9.5	11.5	17.5	0.5
	124.35	34	27	0.5	0	1	14.5	11.5	11	0.5
	127.71	46.5	18	5.5	0	6	3	8	10	3
	131.03	38	19.5	5	0	5.5	0.5	17	9.5	5
Saltwick Formation	144.00	66.5	13	3	0.5	2.5	1	6	7.5	0
	148.90									
	154.10									
	155.00									
	155.50									

BROWN MOOR

TABLE 5.3

%

		GARNET	ZIRCON	STAUROLITE	CHLORITOID	KYANITE	APATITE	RUTILE	TOURMALINE	SPHENE
Kellaways Rock and Sand	63.13	25.5	37.5	5.5	0	15.5	1	4	7	4
	65.10	37	36.5	0.5	0.5	4	2.5	7	12	0
	66.81	7.0	61	2.5	0	8.5	0	13	8	0
	68.69	8.5	34	2.5	0	4.5	1	12	37.5	0
Upper Estuarine Series	73.45	26.5	16.5	0.5	P	P	0	37.5	18.5	0.5
	76.33	30.5	28.5	2.5	1.5	0.5	0	23.5	13	0
Lincolnshire Limestone Formation	80.70	37.5	31	5.5	0.5	1	0.5	12	10	2
	80.93	23.5	29	2	P	1	0.5	22	21.5	0.5

SOUTH CAVE

Brantingham Formation	82.87	POOR ASSEMBLAGES								
	88.40	POOR ASSEMBLAGES								
	91.26	37.5	33.5	1.5	0	2.5	0.5	7.5	17	0
Kellaways Rock and Sand	92.18	19.5	58	6	P	2.5	0	8	3.5	2.5
	95.04	20.5	38.5	8	0	2	0	20	10	1
	98.74	17	31.5	7	0	1	0	22.5	19	2
Upper Estuarine Series	101.44	0.5	43.5	4.5	P	7	0	25.5	18.5	0.5
	102.00	1	21	10.5	0	13.5	0	34	19.5	0.5
	110.33	1.5	22.5	13	0	31.5	0	19	12	0.5
	112.2	9	32.5	6.5	0	31.5	0	16.5	4	0
	117.33									

ALANDALE

TABLE 5.4

Thin section point count data for the Middle Jurassic sandstones of the Nettleton Bottom Borehole (200 grain count). % grains

DEPTH (metres)	Qm	Qp	K	P	M	Py	Ma	A	C	B	D	S	Ch	Co
312.5	46	3.5	8.5					0.5	41.5					
313.5	44		7		0.5		45	0.5	3					
314.8	80	0.5	4.5						3.5		5.5	6		
316.7	74	0.5	10						15.5					
319.5	72		9	0.5	0.5				18					
326.5	74	6.5	0.5		0.5		18	0.5						
326.7	72	0.5	P				0.5		27					
339.0	42						58							
340.5	76	0.5					23.5							
342.5	56	1	11.5		2	1.5	26.5	1.5						
345.5	29.5		5			6.5	31	1	27					
366.7	65	2.5	16.5	2.5	1		12		0.5		P			
367.0	47	2.5	7				1		41.5	1				
367.5	56.5	1.5	13.5		2	1	11.5	1.5			12			
368.5	67	1	10		4	1	16	1						
372	35.5	1	11			0.5	4.5	1.5	41	5		P		
372.7	55.5	1.5	13				3.5	0.5	25.5	0.5				
374.9	60.5	0.5	2		0.5	1	35	0.5						
377	80	3			3	1.5	10.5	2						
379.5	65.5	1.5		1.5	1		30.5							
381	53.5	0.5				1	28	1	16					
381.6	61	3.5			1	3	19	0.5	2			10		
384	52	1.5			1	1	42	0.5	2			P		
388.8	36		0.5			4.5	1.5		0.5	1.5		26.5	29	
389.2	49			1		7	29.5	1					10	2.5
390.1	48	6		1.5	1	3	37.5					P	1.5	1
391.6	25	2.5			3	0.5	14	0.5	19.5			34	1	

Table 5.5

Thin section point count data for the Middle Jurassic sandstones of the Brown Moor Borehole (200 grain count). % grains.

DEPTH metres	Qm	Qp	K	P	M	Py	Ma	A	C	B	S	O
57.80	40.5	00	13.5	1	00	5	26		10.5	4.5		
65.00	40.5	2	13	00	0.5	1	25	3	1			
70.10	28.5	0.5	12.5	00	2	3.5	16.5	1	27.5			
75.00	34.5	1	10.5		0.5	2.5		0.5	42.5			
80.01	38.0		12	1.5	1	10	15		27.5			
92.00	53.5	3	4.5	1				0.5	37.5			
95.39	52.5	5.5	2				5	0.5	34			
96.31	61.5	3.5	4		2.5	5	22	0.5				
97.17	56	3	3		0.5	21	15.5	1				
99.50	66	1	9		7	2	14.5	0.5				
101.80	50.5		11.5	0.5	4	2.5	19.5	1.5				
102.63	56.5		11.5		3.5	0.5	26	1				
104.80	62.5		11		3.5	4.5	16.5	2	3.5			
105.69	47		15		3	12.5	21.5	1	3			
106.31	46		16	1	0.5	7.5	22	0.5	6.5			
108	57.5		14.5		2.5	4.5	15	1.5				
108.60	70	1.5	14.5	1		1	7	1			4	
110.69	48	0.5	13		0.5		13.5	1.5	16			
112.42	51.5	0.5	25	2	3	2.5	9	0.5	6			
117.76	43		11	1.5	3	9.5	5.5	0.5				24
124.35	49		18	0.5	0.5	4	21		7			
127.71	75.5	1	12	1	1	1.5	6.5	1.5				
131.30	63	1.5	7	0.5	1.5	12.5	13.5	0.5				
140.71	36	2	7.5	0.5		1.5		0.5	48	4		
144.00	51		12	1	6	1	28	0.5				
155.00	21		2.5			3.5	52.5		5			15.5
155.50	21.5	6	5.5			2.5	44.5					20

TABLE 5.6

Qm quartz, monocrystalline. Qp quartz, polycrystalline + rock fragments. K Potash feldspar. P Plagioclase feldspar.M Mica. Py Pyrite. Ma Matrix. A Accessory. C Cement. B Bioclasts. D Dolomite. S Siderite. Ch Chamosite. Co Collophane. O Ooliths.

CHAPTER 6

Oxfordian - Kimmeridgian stratigraphy of five shallow cored boreholes in the northern part of the Southern North Sea Basin.

Oxfordian - Kimmeridgian stratigraphy of five shallow cored boreholes in the northern part of the Southern North Sea Basin (Quadrants 42 and 47).

6.1. Introduction

In 1981-82, a series of shallow cored boreholes was drilled, in the southern North Sea, by the Marine Geology Research Group of the British Geological Survey in order to identify the sub-Drift outcrop. This data is subsequently used to improve the interpretation of the shallow seismic data used in the preparation of the 1:250,000 series solid geology maps of the U.K. continental shelf (e.g Lott 1985, Enclosure 1). Three of these borehole cored Kimmeridgian strata (boreholes 81/43, 81/47, 81/49), a fourth cored Kimmeridgian and Oxfordian sediments (81/41) and the fifth borehole (82/18) also cored Oxfordian strata. The location of the five boreholes is shown in Figure 6.1. The boreholes were sited in North Sea quadrants 42 and 47 on the 1:250,000 California (Lott 1985) and Spurn Sheets (Crosby 1985).

Although core recovery was imperfect, the cores show that the lithological and macrofaunal sequences are closely similar to those known in detail from onshore sections in southern and central England where the Kimmeridge Clay consists of rhythmic sequences of silty mudstones, bituminous mudstone and oil shale, medium and dark grey fissile mudstones and pale grey, calcareous mudstone with cementstone. Study of sections from

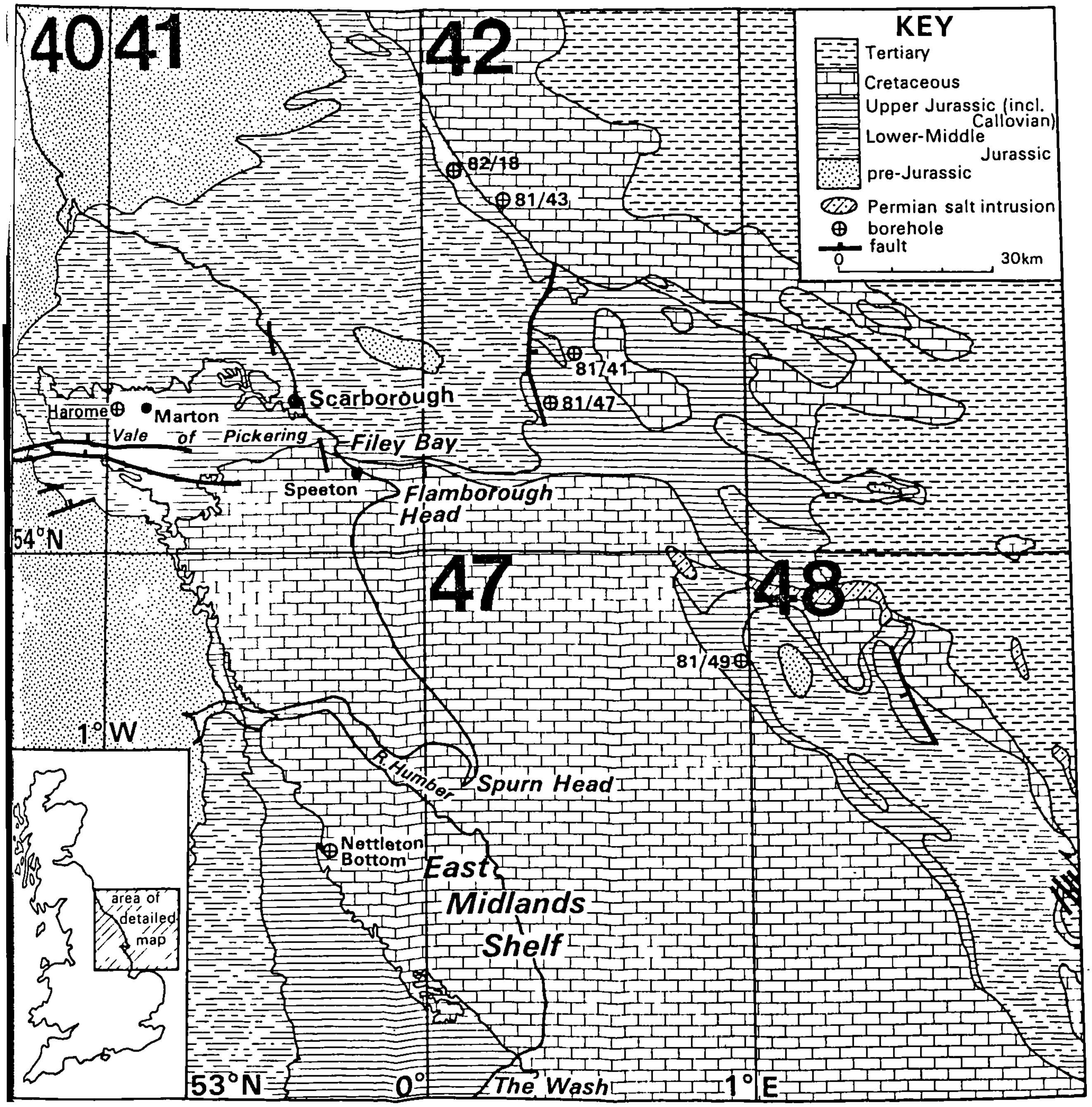


Figure 6.1 Location of the boreholes.

the Dorset coast to Humberside and limited data from the Cleveland Basin indicate that the lithological and macrofaunal sequences are remarkably constant over large areas (Cox & Gallois 1981; Dr B.M.Cox pers comm. 1984) . The stratigraphy of the offshore boreholes drilled by B.G.S. suggest that this uniformity persists into the U.K. sector of the North Sea (Cox et al. in prep.).

6.2. Stratigraphy of the boreholes

The stratigraphy of the five boreholes is described in the following sections. Details of the biostratigraphy and fauna of the sequences are included in Cox et al in prep.

6.2.1. Borehole 81/41 (54/+00/593)

lat. 54^{0}22.197'N long. 0^{0} 27.284'E

Borehole 81/41 cored a 53.1m sequence of Upper Jurassic strata beneath a 14m thick Quaternary cover (Figure 6.2). The Kimmeridgian sequence cored comprised c.32m (14-46m below seabed) of dark grey mudstones with a Lower Kimmeridgian (baylei to mutabilis Zone) macrofauna of bivalves and ammonites. The borehole was sited close to a major north - south listric fracture (the Central Fracture; Enclosure 1) and consequently the area shows considerable secondary faulting and fracturing associated with the main structure. In the borehole (Fig 6.3; see also Fig.3 Cox et al. in prep) the sequence shows evidence of this faulting with the development of high angle calcite beef filled veins.

Underlying this Lower Kimmeridgian sequence is c.9.5m (46-55.50m) of mudstones with thin limestones assigned to the Upper Oxfordian Ampthill Clay (Cox et al. in prep). Calcite beef veins are again evident. The basal metre of this interval consists of bioturbated sandy mudstones, with lignitic fragments. This thin sequence of mudstones compares with c.48m of Oxfordian mudstones in the Cleveland Basin (Cox and Richardson 1982) and it

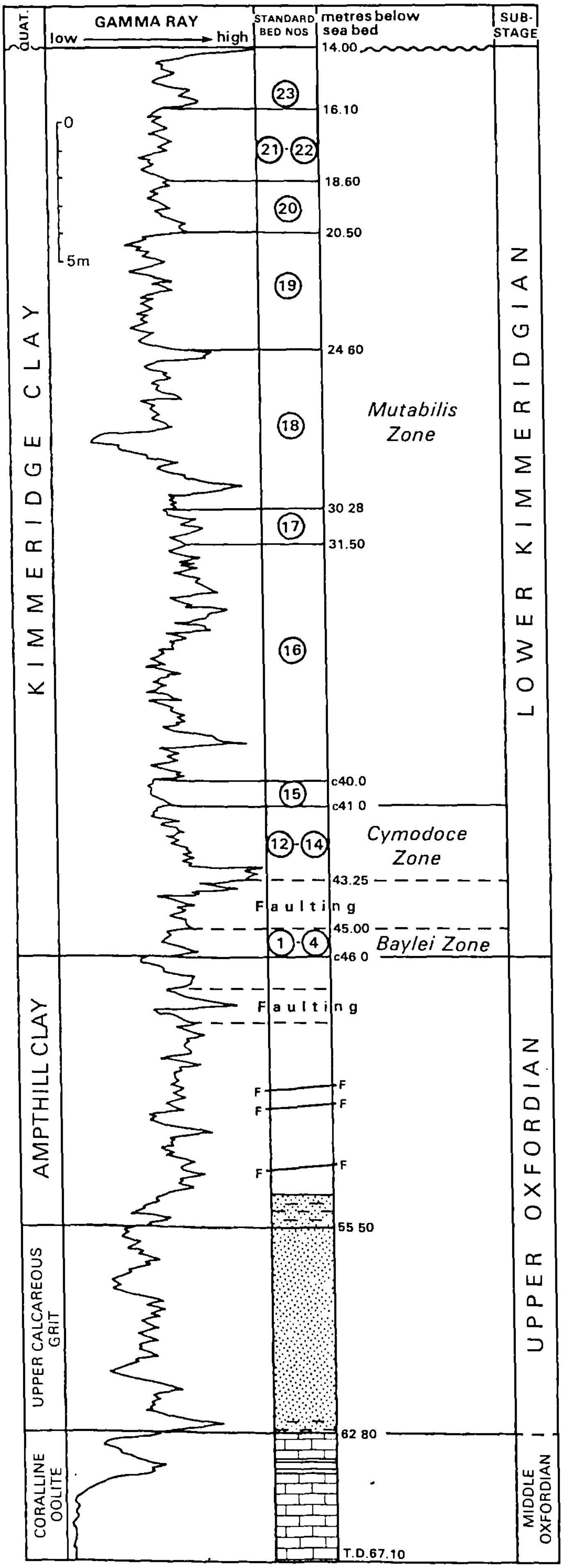


Figure 6.2 Summary log of the stratigraphy of borehole 81/41.

therefore seems likely that much of the sequence has been faulted out at the borehole site.

The interval 55.50 - 62.80m comprises 7.30m of pale grey, very fine sandstones assigned to the Upper **Calcareous Grit Formation.** The sandstones vary from soft, friable units to hard, well cemented, calcareous sandstones. The sandstones are bioturbated, non-fossiliferous and become more muddy towards the base of the interval before passing into oolitic limestones.

The basal interval in the borehole (62.80 - 67.10m T.D.) comprises a sequence of pale grey to white oolitic and bioclastic limestones, interbedded at the top with thin, pale clay bands. The limestones are assigned to the **Coralline Oolite Formation** (Corallian Formation of Rhys 1974) on the basis of their lithology. In thin section the limestones are composed of well rounded intraclasts, ooliths, pisoliths and bioclastic debris in a sparry calcite matrix.

6.2.2. Borehole 82/18 (54/+00/621)

lat. 54^{0}42.551'N long. 0^{0}4.997'E

The borehole was sited on a prominent topographic ridge at seabed to determine whether this feature, which is mappable over much of the area, is formed by the outcrop of the Coralline Oolite. The borehole cored 15.5m of Quaternary sediments before penetrating oolitic limestones. Only 3.6m of these limestones were cored before the hole was abandoned because of drilling difficulties. The core recovered consists of grey to buff coloured oolitic limestones. Bioclastic debris is common and the limestones are frequently stylolitic. The limestones are assigned to the Middle Oxfordian, **Coralline Oolite Formation** on lithological grounds. In thin section the limestones are grainstones and are variably oolitic. Thin-walled bivalves are common along with other bioclastic debris, often set in a sparry calcite matrix.

6.2.3. Borehole 81/43 (54/+00/595)

lat. 54°38.919' long. 0°14.509'E

In borehole 81/43, only a few metres of Kimmeridge Clay were cored below the Coprolite Bed which marks the base of the Lower Cretaceous, Speeton Clay Formation, at a depth of c.90m (Figure 7.2; Chapter 7). The strata cored comprise c.2.9m of dark grey oil-shale, interbedded with bituminous mudstone and medium to dark grey mudstones. They are overlain by 1.33m of pale grey, highly calcareous mudstone. The sequence is assigned to the Upper Kimmeridgian (hudlestoni - wheatleyensis zones) on the basis of its rich fauna of bivalves and ammonites.

6.2.4. Borehole 81/47 (54/+00/598)

lat. 54°16.586'N long. 0°23.168'E

Borehole 81/47 cored a sequence of Kimmeridge Clay (autissiodorensis - scitulus zones), 26.3m thick, beneath c.6m of Quaternary sediments (Figure 6.4) (Cox et al in prep). The sequence consists of medium and dark grey mudstones, interbedded with fissile, brownish grey, bituminous mudstone and oil-shale; more rarely pale or very pale grey calcareous mudstone occurs. A single thin cementstone horizon occurs at 10.90-11.02m. The sequence yielded good assemblages of bivalves and ammonites.

6.2.5. Borehole 81/49 (54/+00/1231)

lat. 53°48.149'N long. 0°58.591'E

Borehole 81/49 was sited on the Jurassic outcrop along the western margin of the Sole Pit Trough to help determine the stratigraphy of the Jurassic sediments which dip westwards beneath a thick Cretaceous cover (Figure 6.5). The borehole cored a 12.7m thick sequence of Lower Kimmeridgian mudstones (eudoxus Zone) beneath 11.30m of Quaternary sediments. The sequence comprises medium grey, fissile, shelly mudstones,

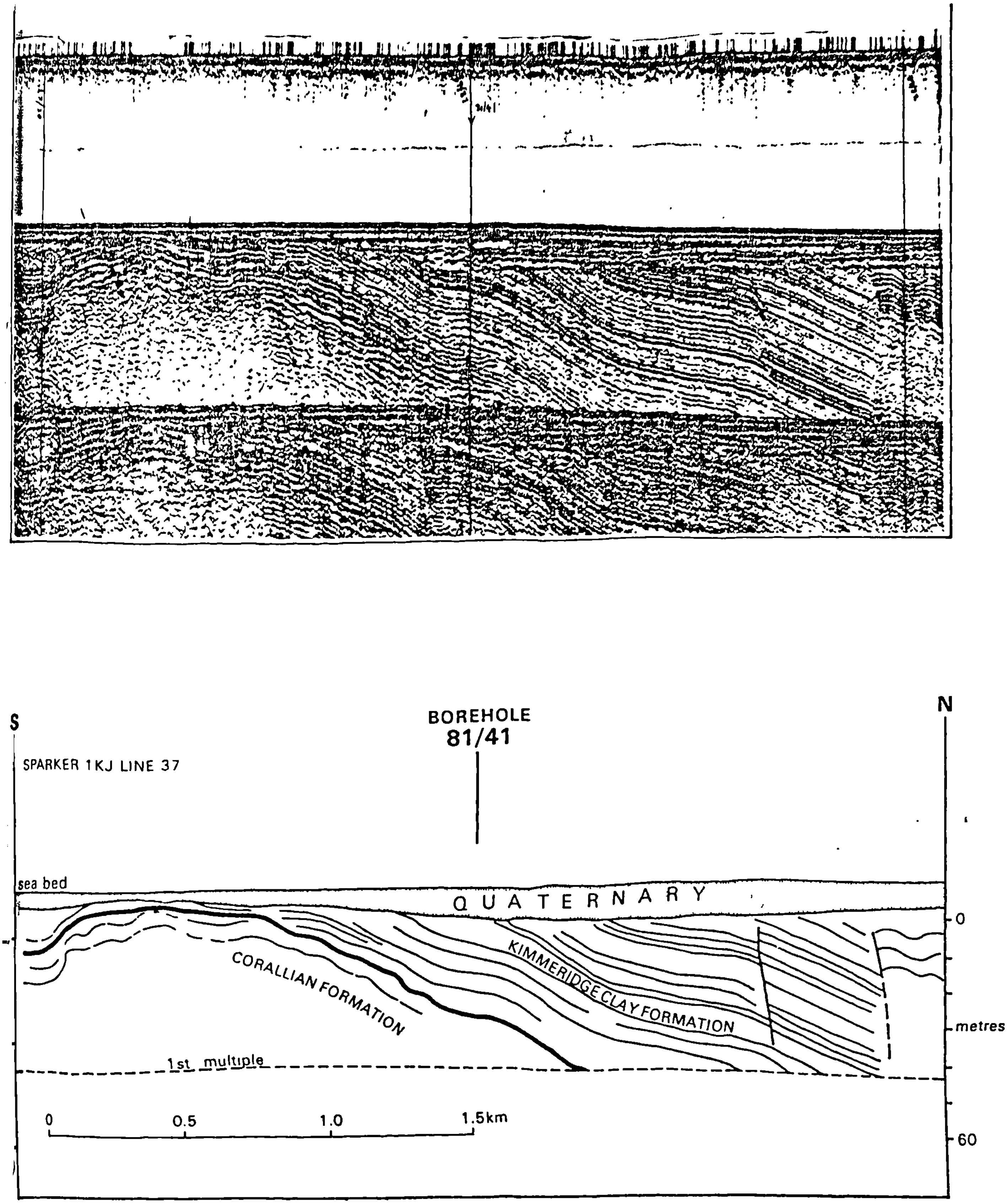


Figure 6.3 Sparker seismic profile through the site of borehole 81/41.

oil-shale and thin interbeds of pale and very pale grey calcareous mudstones. A rich macrofauna of bivalves and ammonites was obtained from the mudstones.

Conclusions

6.3.1. **Middle to Upper Oxfordian** (see also Chapter 4)

No core material is available from the Oxfordian sequences in the Southern North Sea Basin, with the exception of short cores from the oolitic facies of the Corallian Formation. Subdivision of the succession is therefore largely based on wireline log interpretation (Chapter 4). A number of wells from the offshore area have proved thick sequences of spiculitic sands (Lower Calcareous Grit Formation), overlain by oolitic limestones which can generally be assigned to the Coralline Oolite Formation on lithological grounds. The greatest preserved thicknesses of Corallian oolitic limestones penetrated (c 70m) were proved in wells 47/9-3 and 48/7b-4 sited along the Sole Pit Trough (Figure 4.9). Upper Oxfordian sediments were proved in borehole 81/41 where they comprised a thin sequence of sandstone (Upper Calcareous Grit Formation) and a thin Ampthill Clay sequence. The oolitic limestone facies, which is well developed in the offshore area, is now generally considered to represent only the littoral facies of the Middle Oxfordian with more open marine conditions typified by the the mudstone and siltstone facies of the West Walton Beds (Gallois and Cox 1977).

6.3.2. **Kimmeridgian**

The Kimmeridge Clay type organic rich mudstone facies cored in the BGS boreholes were deposited in a shallow marine environment which covered much of the North Sea area. Kimmeridgian strata therefore have an extensive subcrop beneath Cretaceous strata over the Southern North Sea Basin (Figure 3.6). The Kimmeridge Clay sampled offshore is closely comparable with the

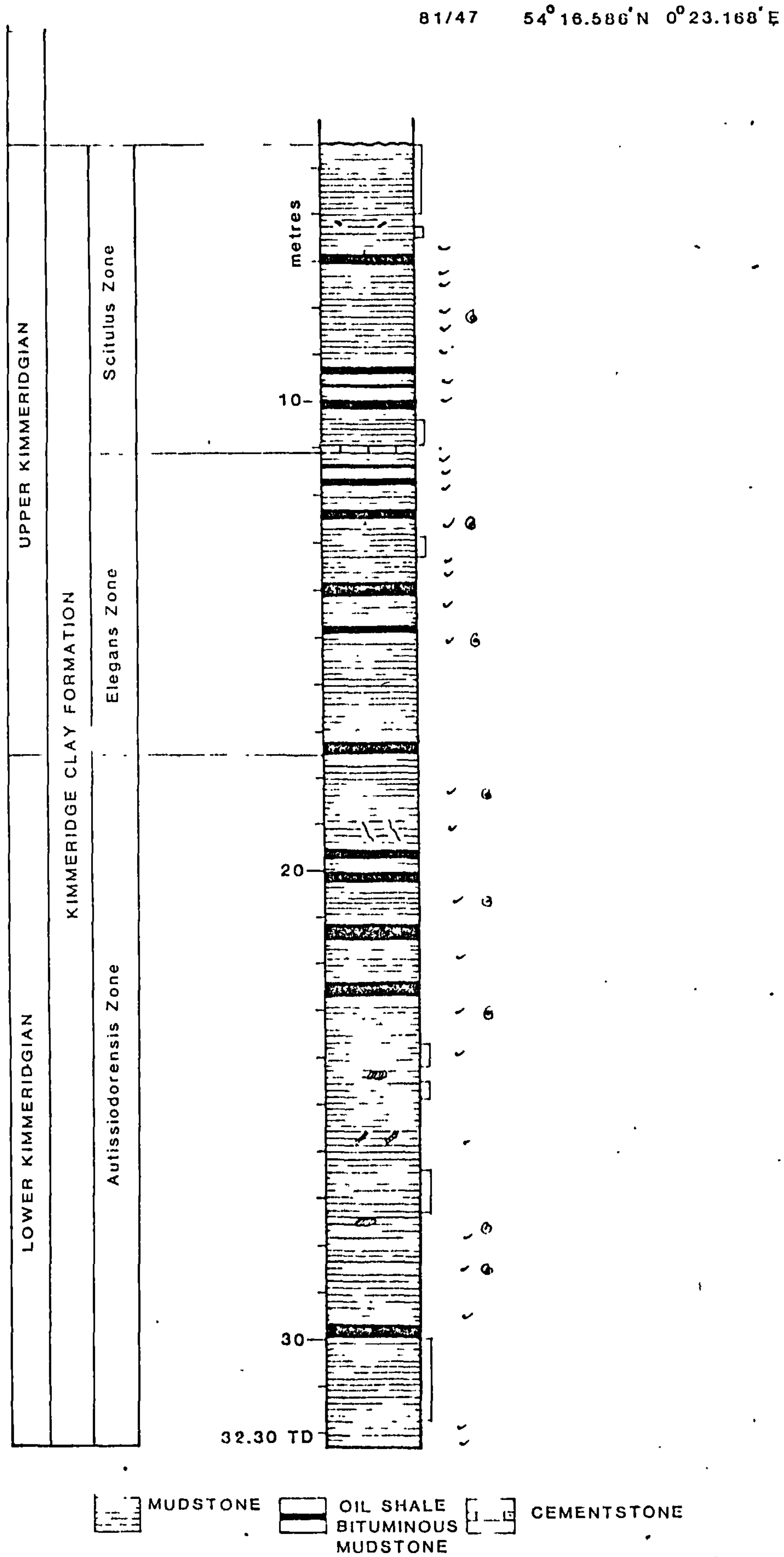


Figure 6.4 Summary log of the stratigraphy of borehole 81/47.

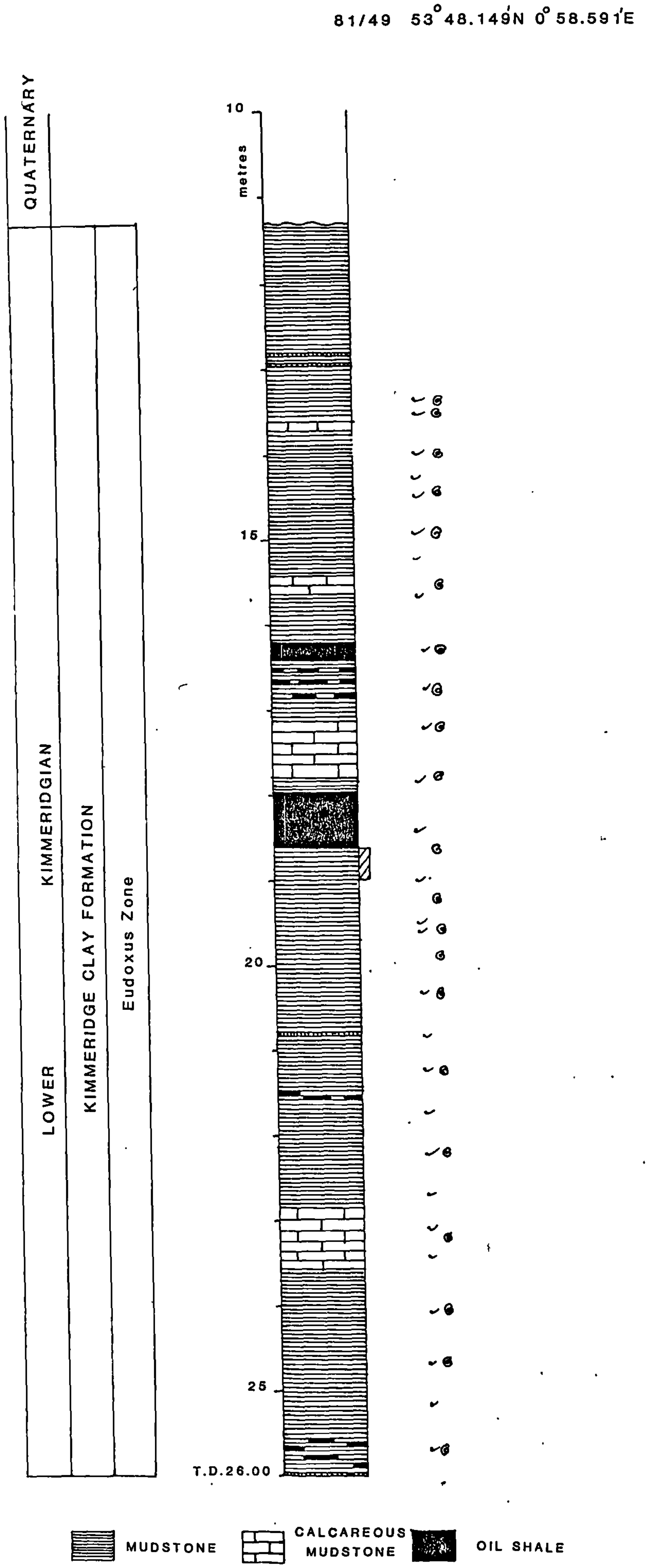


Figure 6.5 Summary log of the stratigraphy of borehole81/49.

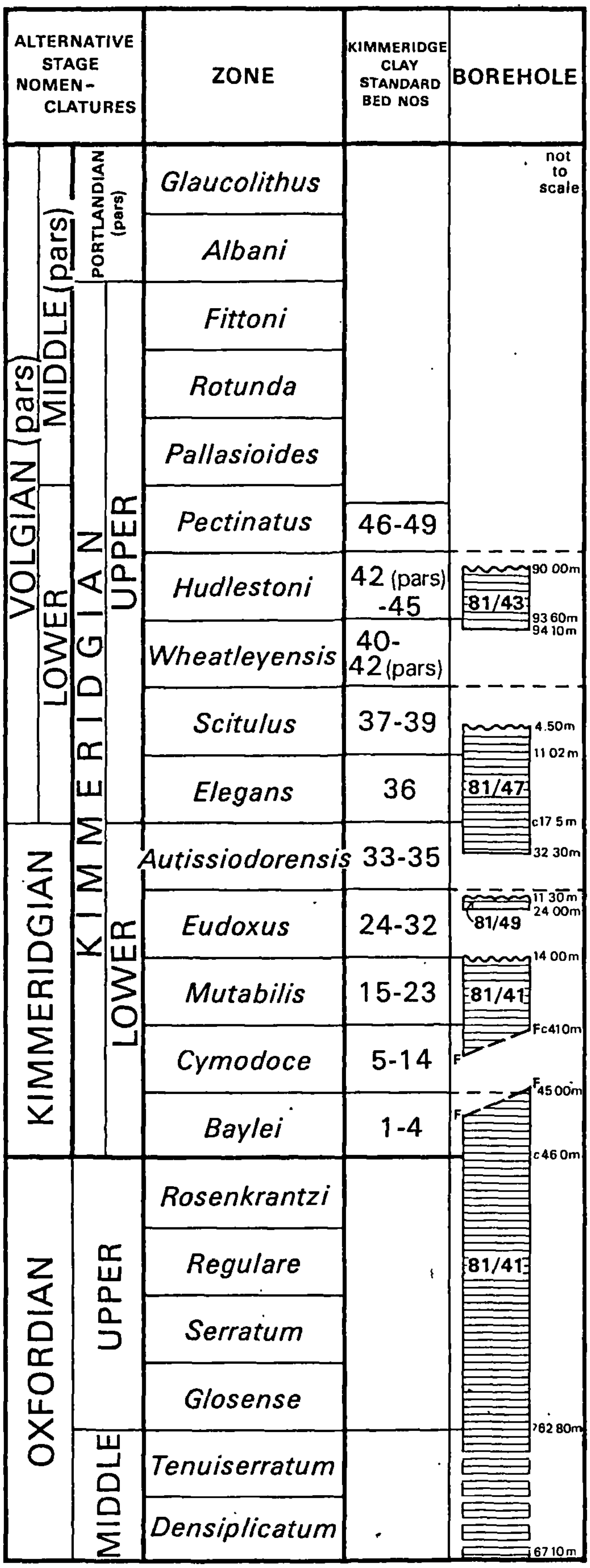


Figure 6.6 Stratigraphic relationship of the Kimmeridgian sequences cored in the southern North Sea.

onshore succession, both lithologically and stratigraphically. The rhythmic cycles of sedimentation described by Gallois (1976) are readily apparent in the cored sequences. The Kimmeridge Clay sequence of the type succession has been divided into a series of numbered beds, which are recognised throughout the onshore outcrop, on the basis of their lithology and associated faunal assemblages (Cox and Gallois 1981). Dr. B. M. Cox has examined the macrofaunas collected from the boreholes and has extended the recognition of some of the more prominent marker beds into the offshore area (Figure 6.6) (Cox et al in prep). The stratigraphy of these clay sequences has become of particular interest since the realisation that much of the oil in the Northern North Sea oilfields was sourced from Kimmeridgian mudstones. The biostratigraphy of the Kimmeridgian successions north of the Mid-North Sea High is, however, still only poorly known and correlation between this northern area and the type succession are still extremely tentative.

CHAPTER 7

The stratigraphy of the Lower Cretaceous Speeton Clay Formation, from a cored borehole off the coast of north-east England.

The stratigraphy of the Lower Cretaceous Speeton Clay Formation, from a cored borehole off the coast of north-east England

7.1. Introduction

The Speeton Clay Formation (Rhys 1974; Rawson et al 1978) of north-east Yorkshire is known to extend offshore into the Southern North Sea Basin and has been proved in a number of offshore commercial wells in the southern part of quadrant 42, but never cored (Figure 7.1) (Dingle 1971; Rhys 1974; Kent 1980b; Rawson and Riley 1982).

During 1980/81 the British Geological Survey (BGS), funded by the Department of Energy, undertook a detailed shallow seismic survey of the southern North Sea area as part of its offshore regional mapping programme. In order to aid the interpretation of these seismic data, a number of shallow cored boreholes were drilled in selected parts of the Mesozoic and Tertiary sequences of the basin.

One of these boreholes, BGS borehole 81/43 (54°38.919'N, 0°14.509'E), was drilled 80 km ENE of Speeton cliffs, in Block 42/12; it fully cored an 89.87m sequence of dark greenish-grey, calcareous clays and brownish-black, occasionally organic-rich and non-calcareous mudstones of Lower Cretaceous age (Speeton Clay Formation). These clays rest on 4.23m of dark olive grey mudstones of Jurassic age (Figure 7.2, 9.9).

A comparison of the microfaunas of this offshore Lower Cretaceous sequence with those at the type section of the Speeton Clay, in Filey Bay, Yorkshire has shown that these marine clays range from Ryazanian to Barremian.

The clays compare closely, both lithologically and sedimentologically, with the type section and present a unique opportunity to compare and

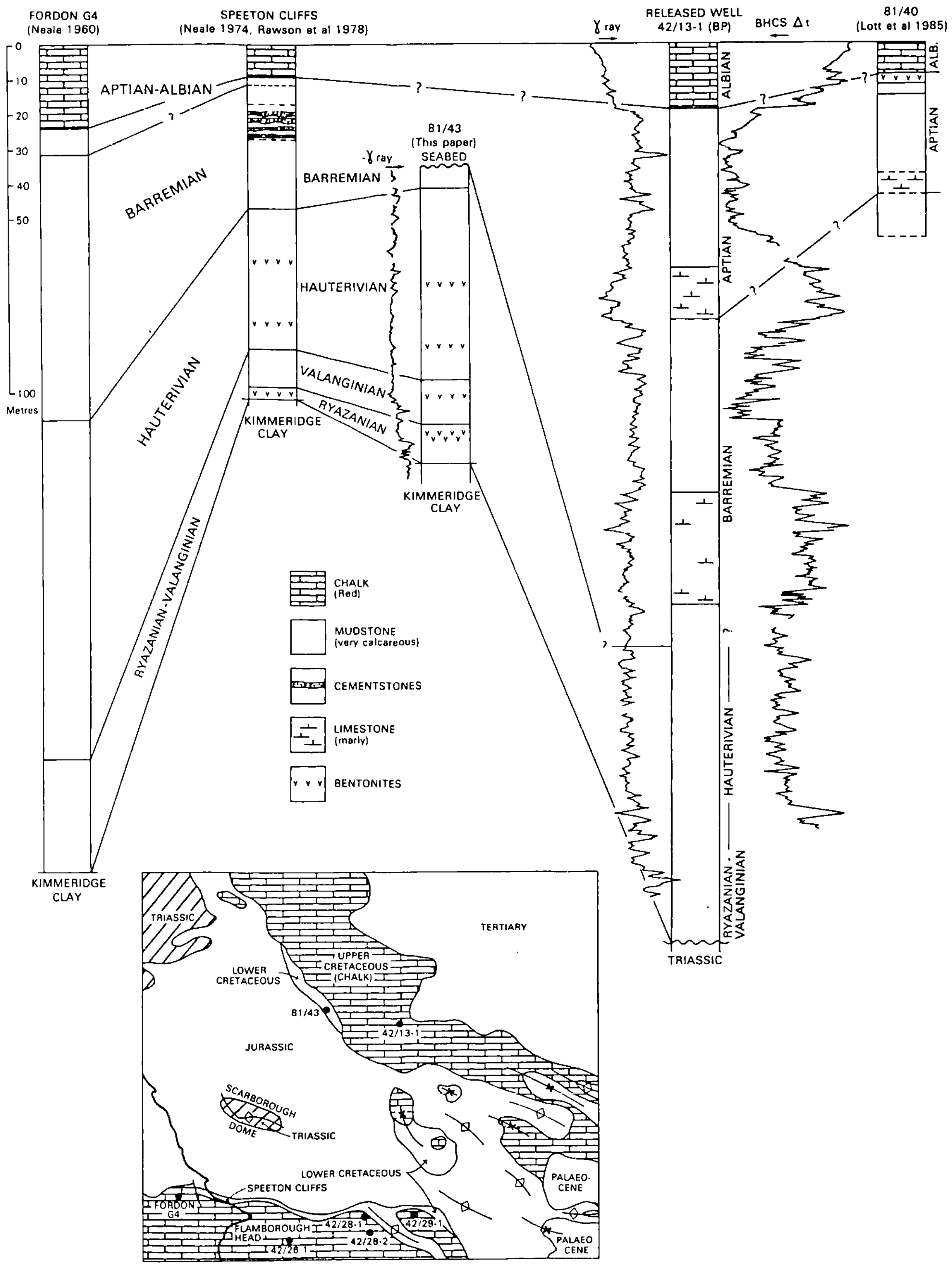


Figure 7.1 Borehole location and correlation of the sequence with adjacent areas

relate the stratigraphy of the offshore North Sea area to that of the type sequence at Speeton, without the complications often presented in the Speeton cliffs by landslipping and weathering and the intermittent exposure of the succession.

The stratigraphy of the borehole presented here is based upon detailed examination of the microfaunas of the sequence (Lott et al. in press).

7.2. Stratigraphy and the borehole sequence

The Speeton Clay Formation, which crops out on the North Yorkshire coast, is the most complete representative of the marine Lower Cretaceous strata known onshore in Britain. The sequence is generally taken as the stratotype for the marine Boreal Lower Cretaceous of Europe, and consequently has received a considerable amount of attention.

The classic paper on the Speeton Clay is that by Lamplugh (1889) who divided the clays into five units (A, B, C, D and E downwards), on the basis of their belemnite faunas and in the case of unit E (the basal Coprolite bed) on its distinctive lithology. More recent work has produced a more refined division of these basic 5 divisions (Neale 1960, 1968; Kaye 1964; Fletcher 1969, 1973; Rawson 1971; Rawson and Mutterlose 1983).

In the offshore sequence in borehole 81/43, representatives of the B, C, D and E beds of the Speeton cliff succession have been cored and a detailed examination has enabled many of the minor subdivisions known at Speeton to be recognised.

In addition to the extremely good biostratigraphic control of the sequence a number of distinct lithological markers can be distinguished in the borehole and are used to demonstrate further correlations between the two sequences. These marker horizons include seven thin bentonite bands and a number of coccolith-rich limestone bands, most of which have representatives recognisable in the onshore succession. The borehole was drilled using the chartered drilling ship **m. v. Mariner**, in a water depth of 67m, and obtained core of 100mm (4 inch) diameter.

The borehole drilled 4.50 metres of sand at the seabed before entering the Speeton Clay Formation, and the borehole was terminated at 94.10m in Kimmeridge Clay. All depths are measured from the sea bed. The borehole was subsequently sub-sampled at approximately 0.5m intervals for micropalaeontological examination.

Shallow seismic profiles across the Kimmeridge Clay / Speeton Clay boundary in the area show a low angle unconformity separating the two formations.

7.3. Jurassic: Kimmeridge Clay Formation

7.3.1. Upper Kimmeridgian 89.87-94.10m (the borehole Terminal Depth - TD.)

The oldest strata penetrated in the borehole consists of 4.23m of pale olive to brownish-black, bituminous mudstones of Late Jurassic age. The upper 0.39m of these beds are dark, friable calcareous mudstones, cross-cut by a number of thin calcite - filled fractures and penetrated by large vertical borings, 150-200mm in length, which pipe down small shiny phosphatic pebbles from the overlying Coprolite Bed. The faunal assemblage is indicative of the Hudlestoni Zone, Reisiformis Subzone of the Upper Kimmeridgian; it includes the ammonites Pectinatites (Virgatosphinctoides) cf. donovani Cope and P. (V.) cf. reisiformis Cope. The Kimmeridgian sequence proved in the borehole probably falls in Beds 42-44 of the standard Kimmeridge Clay sequence (Cox & Gallois 1979, 1981; Dr B. M .Cox, pers. comm. 1984).

On the Yorkshire coast, in the Speeton cliffs, the Kimmeridgian mudstones are exposed, from time to time, at beach level. The beds belong to the Pectinatus Zone, Eastlecottenensis Subzone (Cope 1974) and are thus younger than the Kimmeridge Clay in the borehole, indicating the transgressive nature of the Coprolite Bed and the presence of an important stratigraphic break at this level. The Kimmeridgian stratigraphy from this and a number of other cored boreholes in the southern North Sea area is discussed in detail in Cox et al. (in prep.).

7.4. Cretaceous: Speeton Clay Formation.

7.4.1. The Coprolite Bed (Bed E) 89.75-89.87m

The base of the Cretaceous sediments in the borehole is marked by a thin phosphatic conglomerate, the Coprolite Bed (120mm). This dark grey, hard conglomeratic unit consists of angular clasts of olive-grey calcareous mudstone (possibly derived from the underlying Kimmeridge Clay) together with black, shiny, phosphatic subrounded pebbles, pyrite, and belemnite fragments in a non-calcareous muddy matrix. The phosphate pebbles range up to 10mm across and show a distinctive polished, black patina; similar granule-sized grains also occur some distance above the top of the Coprolite Bed.

At the base of the unit there is a thin black clay 10mm thick, packed with shiny, black phosphatic granules. The top of the unit is sharply defined. At Speeton the Coprolite Bed is "a thin stony band of black phosphatised nodules" (Lamplugh 1889). It averages 100mm in thickness and contains "numbers of black phosphatic pebbles . . . . caked together in a matrix" (Lamplugh, op cit.). In the coastal sequence the phosphatic nodules have yielded indeterminate ammonites (Rawson et al. 1978); however, in the borehole the Coprolite Bed contained only rare belemnite fragments. This basal Coprolite Bed has only been described previously from the Speeton cliffs succession, and this is the first proved identification of the bed in the North Sea basin. The similarity in both thickness and lithology of the bed in this offshore borehole with that at Speeton, 80km away, is remarkable.

7.4.2. Laminated mudstones and siltstones (Bed D8) 82.99-89.75m.

The strata of this unit immediately overlie the Coprolite Bed and consist of hard, non-calcareous, dark-grey to black, bituminous mudstones, with thin paler interbedded siltstones. When initially recovered, these mudstones were characterised by a strong bituminous smell. Pyritic and phosphatic nodules occur at the base of the unit, together with rare, small shiny phosphatic pebbles. The beds show rare burrows and are non-fissile despite their obvious fine lamination. Variations in silt content produce a subtle pale to dark colour-banding throughout the unit. The beds yielded a sparse fauna consisting of poorly preserved belemnites, fish-debris, radiolarians and agglutinated foraminifera. The top of the unit is marked by a large phosphatic concretion and a significant concentration of silt and sand laminae. Above this boundary the sediments are markedly paler and non-bituminous although they remain non-calcareous and silty.

At Speeton cliffs these black bituminous mudstones and siltstones are represented by a thin (0.30m) 'Black Shale' unit (Bed D8) immediately overlying the Coprolite Bed (Neale 1962, 1974). Though considerably thinner than their offshore equivalents these beds show a similar restricted fauna. Attention has been drawn by Neale (1968) to the absence of bioturbation and consequent retention of the primary fine lamination of the unit at Speeton - a feature rare in the heavily burrow-mottled clays which comprise the main part of the formation.

7.4.3. Calcareous clays (Beds D7- LB 6) 4.50-82.99m

The greater part of the cored Speeton Clay Formation consists of dark greenish-grey, very calcareous non-fissile clays which are closely comparable with the clays and mudstones at Speeton. The clays in the borehole are frequently silty, often with a gritty texture resulting from the profusion of foraminiferal tests and comminuted bioclastic debris that

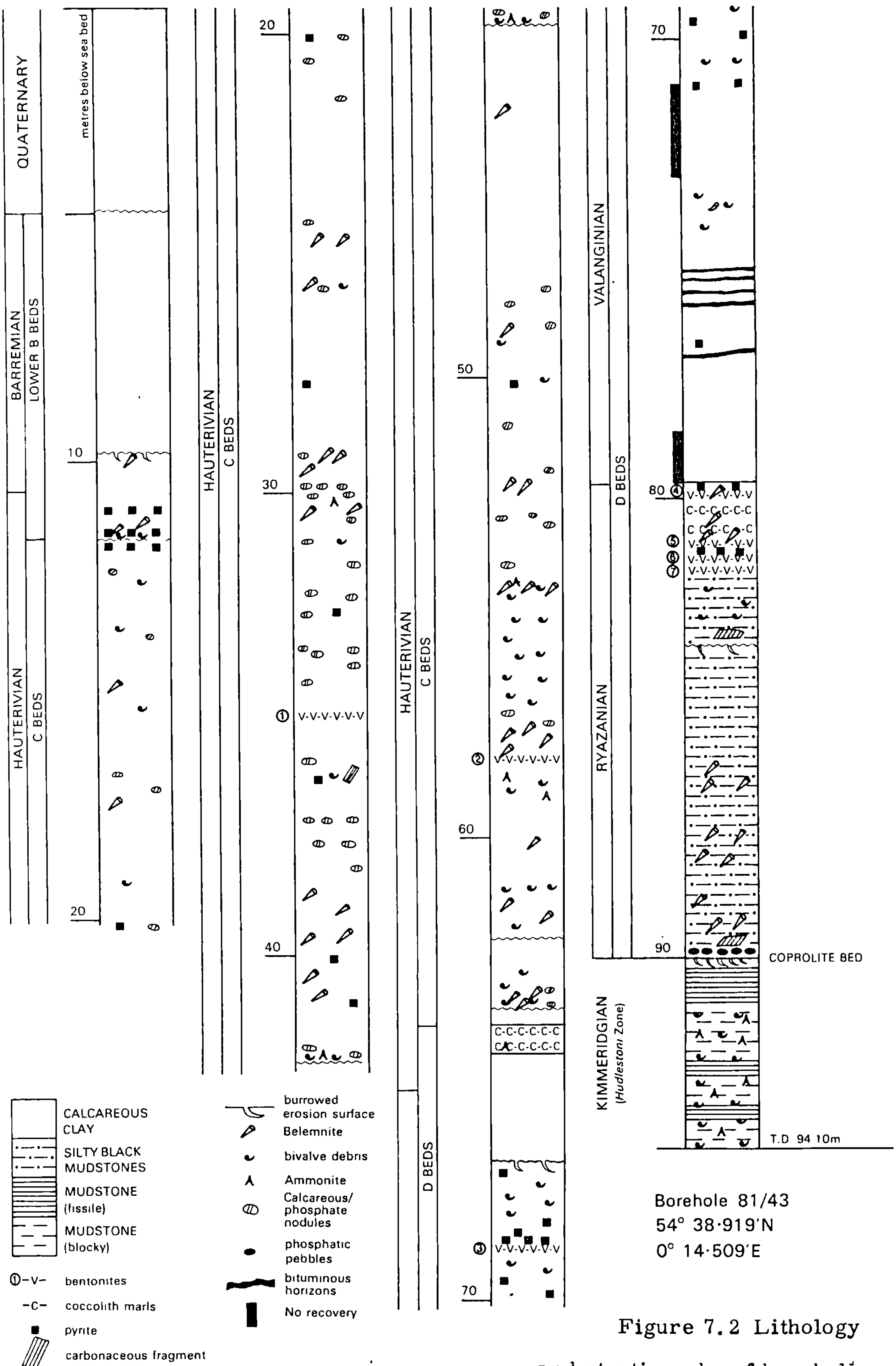


Figure 7.2 Lithology and stratigraphy of borehole 81/43.

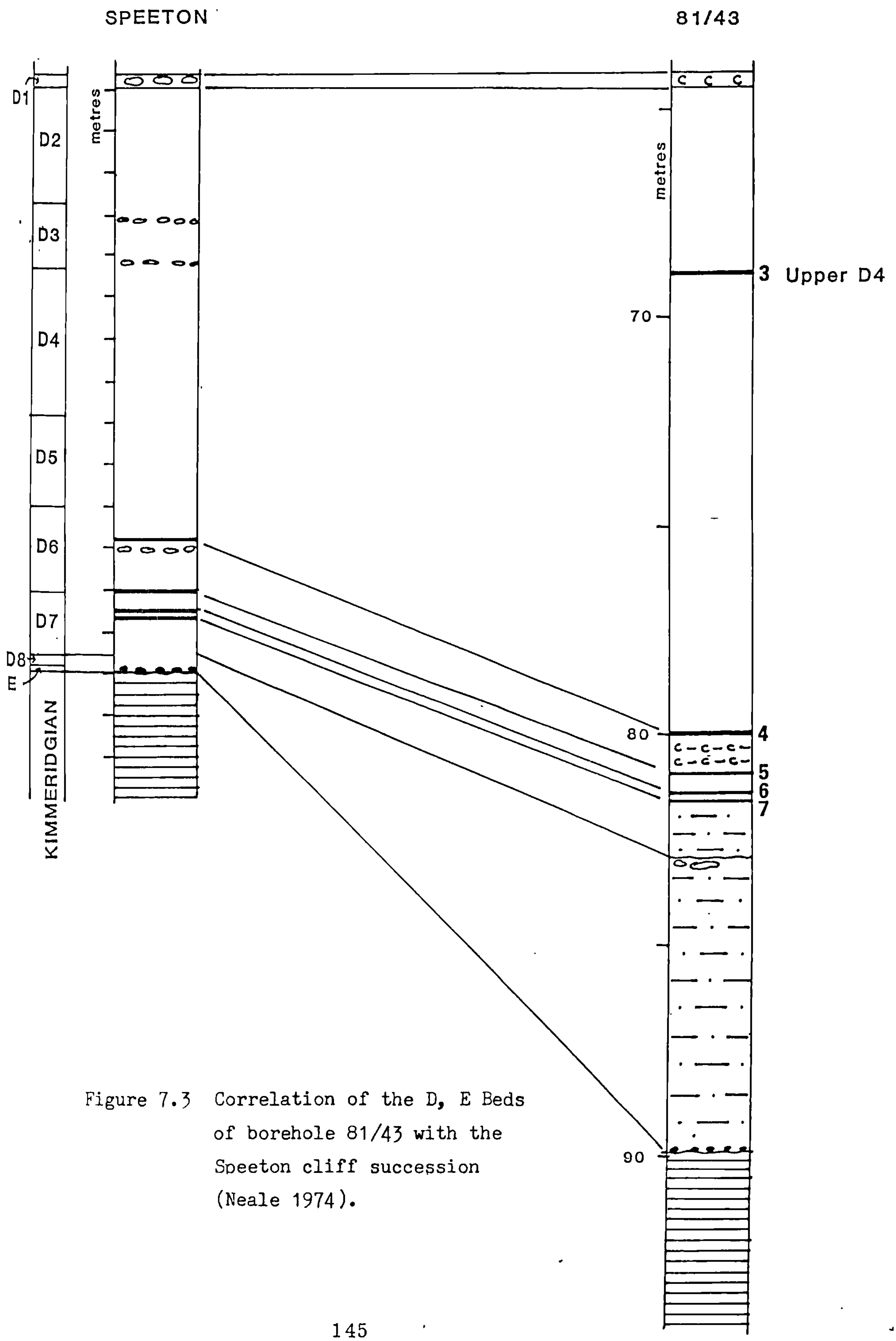


Figure 7.3 Correlation of the D, E Beds of borehole 81/43 with the Speeton cliff succession (Neale 1974).

occurs at various levels throughout the sequence. Strong bioturbation is characteristic of the clays, with Chondrites-type burrow-mottling particularly common. Pale, cream-brown, calcareous and phosphatic nodules up to 30mm in length with a dark brown rim are also common, especially between 30-40m, but become rare below about 63m. Pyritic nodules are moderately abundant throughout the succession, with pyrite also occurring as small euhedral crystals, thin tubular burrowfills and framboids and more rarely in association with carbonised woody fragments. Glauconite and siderite are also common constituents of these clays. Belemnites occur at many levels; bivalve and ammonite fragments occur more rarely. Dr P.F.Rawson (pers. comm. 1984) identified a slightly phosphatised ammonite fragment at 64.46m as Karakaschiceras heteroptychum (Pavlow); he further states that this species is known in the phosphatic nodules of the Early Valanginian bed D2D at Speeton, along with other remanié fossils. The genus Karakaschiceras appears limited to the latest Early Valanginian and earliest Late Valanginian time interval, in both Tethys and North-West Europe. Flattened inner whorls of Aegocrioceras cf. quadratum (Crick) were identified (P. F. R.) at 59.12m. This ammonite is found in beds C7F and C7G at Speeton. A single thin densely phosphatised vertebra was found at 58.71m. At several horizons, notably at 64.07-64.46m, 80.28-80.36m and 80.66-80.72m, pale grey to white, burrow-mottled soft marly limestones are thinly developed. These beds represent extremely rich concentrations of coccoliths (Dr A.W.Medd personal communication 1983) and may correlate with similar such coccolith blooms recognised in the Speeton cliffs sequence (Black 1971). They probably account in part for variations in carbonate content throughout the sequence, and hence for the subtle pale to dark colour banding apparent at some levels.

The light grey calcareous marl unit at 64.07-64.46m can, on the basis of the foraminifera and ostracoda, be equated with the uppermost D beds (D1-D2D), and is thought to be a correlative of the Compound Nodular Bed (D1), an important marker horizon in the coastal sequence, which Black (1971) noted was particularly rich in coccoliths.

The seven bentonite bands which were recorded in the borehole lie within this calcareous clay sequence. The thin bluish-grey bentonites often show burrow-mottling but still retaining sharp tops and bases. The lowest group of four bentonites (bentonites 4-7) can be correlated, by means of their associated foraminiferal assemblages, with those recognised within the lower D beds (Ryazanian) at Speeton (Knox and Fletcher 1978). The three upper bentonite horizons are essentially the same in lithology and composition.

The foraminiferal assemblages associated with bentonite 1 include Hechtina antiqua (Reuss) and Frondicularia simplicissima Dam and equates with the upper C4 beds (Late Hauterivian) at Speeton. The assemblages above and below bentonite 2 are composed of long ranging foraminifera and are only diagnostic of an Early Hauterivian age (Dr B. N. Fletcher pers. comm. 1983). Bentonite 3 with Conorboides valendisensis Bartenstein & Brand, Ammobaculites subcretaceus Cushman & Alexander, Ammodiscus tenuissimus (Guembel) and Glomospira gordialis (Jones & Parker) in the adjacent beds, suggests the equivalent to the upper D4 beds (Valanginian) at Speeton. Two of these bands (bentonites 1 and 2) have subsequently been recognised in the Speeton sequence (Figure 7.4) (Dr R. W. O'B. Knox pers. comm. 1983).

These bentonite horizons provide good marker horizons and should prove useful for correlation across the North Sea Basin. The bentonites of Ryazanian age at Speeton and in the borehole probably correlate with tuffs of similar age in the Schuttorf 3 borehole near Bentheim, North West Germany (Zimmerle 1979).

7.5. Conclusions

The depositional environment of the Speeton Clay Formation has been widely documented (see for example Neale 1974 and Rawson et al. 1978). This generally uniform sequence, in the North Sea area, represents the continuation from the Late Jurassic, of a long period of quiet-water marine clay sedimentation with little or no coarse clastic detritus entering the main basin. The depositional basin extended from eastern England into north-west Germany and northwards into the Central and Viking Grabens. The basin was bounded to the south by the Anglo - Brabant High, a barrier which was apparently unbreached until the Aptian / Albian, and which before this time separated the northern marine clay facies from the largely paralic 'Wealden' sediments of southern and western Britain (Allen 1981). The landmasses supplied little clastic material to this northern basin other than as local sands over in the north Norfolk - East Midlands area (Spilsby Sandstone) and in the Moray Firth and Central Graben areas (Devil's Hole Fm.) (Anderton et al.1979; Deegan and Scull 1977). The clay sequences of the Speeton Clay Formation reach thicknesses of up to 350m in the Southern North Sea Basin but further north (i.e. north of the Mid North Sea High) thicknesses of up to 793m have been recorded for the Cromer Knoll Group as a whole (Deegan and Scull 1977), significantly thicker than the type section in Yorkshire where the equivalent beds are 102m thick.

Initial deposition of the Speeton Clay, following a break in sedimentation during the Late Jurassic - Early Cretaceous, commenced with the accumulation of the thin transgressive remanie Coprolite Bed, consisting of phosphatised, rolled pebbles, fossil fragments and mudstone clasts, all largely derived from erosion of the underlying Kimmeridgian beds. The subsequent transgression across this basal pebble bed is represented in the borehole by an 8 - metre thick sequence of black non-calcareous, silty organic rich mudstones, and at Speeton by 0.3 metres of black mudstones forming bed D8 (Neale 1974). The lithology of these basal mudstones is suggestive of a restricted marine environment with poor circulation and oxygenation of the basin waters during the initial phase of the transgression.

The development of organic-rich shales, such as this basal Cretaceous sequence, at the onset of a marine transgression have been documented from a number of Jurassic sequences (Hallam and Bradshaw 1979) and this sequence is perhaps a comparable case in the Early Cretaceous. It is notable that the area to the east and south-east of the borehole, in the Southern North Sea Basin, is characterised by complex salt tectonics, with the development of a number of large salt structures (Dingle 1971; Lott 1985) which were probably actively developing throughout the Lower Cretaceous and which may therefore have contributed to the restriction of circulation of the basin waters during the initial transgression by forming significant topographic barriers. The fauna of these black mudstones is very limited, only poorly preserved belemnites, agglutinating foraminifera, radiolarians and fish debris are present. The sequence in the borehole shows little evidence of bioturbation, suggesting a restricted benthic fauna. The absence of calcareous microfossils, however, could be attributable to later diagenetic effects; certainly the state of preservation of the belemnites in this lower sequence is very poor. The association of radiolarians with black shale sequences similar to this basal Speeton Clay interval have been documented by a number of authors (see Jenkyns 1980).

The deposition of these basal organic rich mudstones in the borehole is terminated by a further break in sedimentation with the consequent development of large phosphatic concretions at 83m (Figure 7.2) though no faunal change is seen at this level.

In the borehole the beds overlying these concretionary developments show a notable change in lithological character. The sediments become markedly calcareous, paler in colour with only minor organic - rich horizons. A similar change is documented at this horizon in the Speeton sequence. A rich benthonic microfauna and strong bioturbation is also evident throughout the remainder of the borehole sequence. This change appears to represent conditions of improved circulation and oxygenation and perhaps some deepening of the basin waters to overcome the restrictions to circulation imposed by the salt structures in the basin. However, quiet-water conditions of sedimentation continue to characterise this clay sequence, although the original lamination of the sequence has subsequently been destroyed by the intense bioturbation.

The fine microfaunal subdivisions recognised at Speeton cliffs (Fletcher 1973; Neale 1974) can be correlated with those of the borehole with comparatively little difficulty in the lower part of the sequence, (Beds D7-D1), where there is comparatively little change in the thickness of the individual units. In particular the thin bentonite bands in the lower part of the borehole, within the Ryazanian sequence, can be correlated with those described from the succession at Speeton cliffs (Knox and Fletcher 1979) and show remarkably little variation in thickness despite an 80km separation between the locations. Within these lower beds, which correlate with D1-D7E at the coast, occasional thin white marls occur. These beds are coccolith-rich sediments (Dr A. W. Medd pers. comm. 1983) and compare closely with similar coccolith-rich 'blooms' documented from the Kimmeridge Clay (Gallois 1976). Such 'blooms' in the Kimmeridge Clay, are closely associated with oil-shale horizons and, although the the occurrence of organic-rich horizons within the Speeton Clay succession in the borehole are noticeably reduced above the basal black mudstone unit, thin, sooty, bituminous horizons were noted in the core. Bioturbation of these white marly units is very apparent with the darker Chondrites-type burrow-fills, mottling the pale, calcareous matrix.

The dark calcareous clays which characterise the bulk of the disconformably overlying Hauterivian to Barremian interval of the borehole sequence (C Beds - Lower B Beds) contain a rich microfauna. Lithological changes within this part of the sequence are restricted to subtle variations in carbonate content and no major breaks in sedimentation are apparent as a more stable regime of deposition was established in the basin. The thin volcanic tuff bands point to continued spasmodic volcanic activity around the basin throughout the Hauterivian.

The thickness of the Speeton Clay Formation in the Southern North Sea Basin is on the basis of released well data, very variable. Wells sited near the crests of some of the larger salt structures often show thin Lower Cretaceous successions, whereas those in the associated rim-synclinal troughs and along the north-west to south-east trending Dowsing Fault complex show a considerable increase in the thickness of Lower Cretaceous strata - 250m in B. P Well 42/13-1. A comparison of the downhole Gamma Ray log of borehole 81/43 with that of released Well 42/13-1 which lies 25 km to the east suggests that this expansion in thickness may be represented at least in part by the presence of a considerable thickness of Barremian and Aptian sediments. Log correlations between the two boreholes suggests that in addition to the Ryazanian to Early Barremian sediments, c.137m of Early/Late Barremian to Aptian sediments are present in Well 42/13-1, overlain by c.21m of Aptian - Albian red marls and red chalk. A suggested correlation between borehole 81/43 and the expanded Lower Cretaceous sequence in released B. P. well 42/13-1 is shown in Figure 7.1.

CHAPTER 8

Mid-Cretaceous stratigraphy of a cored borehole in the western part of the Central North Sea Basin.

Mid-Cretaceous stratigraphy of a cored borehole in the western part of the Central North Sea Basin

8.1. Introduction

Shallow drilling by the Marine Geology Research Group of the British Geological Survey (BGS) in the Central North Sea (borehole 81/40, $56^{O}08.03'$N $0^{O}43.60'$E), cored a 94m sequence of Cretaceous strata ranging in age from Barremian to Turonian (Figure 8.1). Drilling and coring terminated at a depth of 112.6m. At this site, shallow seismic profiles indicate that there is up to a further 100m of Lower Cretaceous strata unconformably overlying Triassic sediments. Six lithostratigraphical units were recognised within the cored Cretaceous succession of the borehole:

(i) a lower-most unit of calcareous greenish grey, in places brown, mudstones, with paler, hard, limy bands (?Barremian to Middle Aptian).

(ii) calcareous red mudstones (Middle to Late Aptian).

(iii) grey brown mudstones with eight thin volcanic tuff bands (Late Aptian to Early Albian).

(iv) thin variegated silty mudstone beds with a single volcanic tuff band (Early Albian).

(v) a thin 'red chalk' sequence (Middle Albian to Early Cenomanian).

(vi) an uppermost unit of white chalk (Cenomanian to Turonian).

The lithology of each of these units is described in the following account. The sequence yeilded a rich calcareous microfauna of foraminifera and

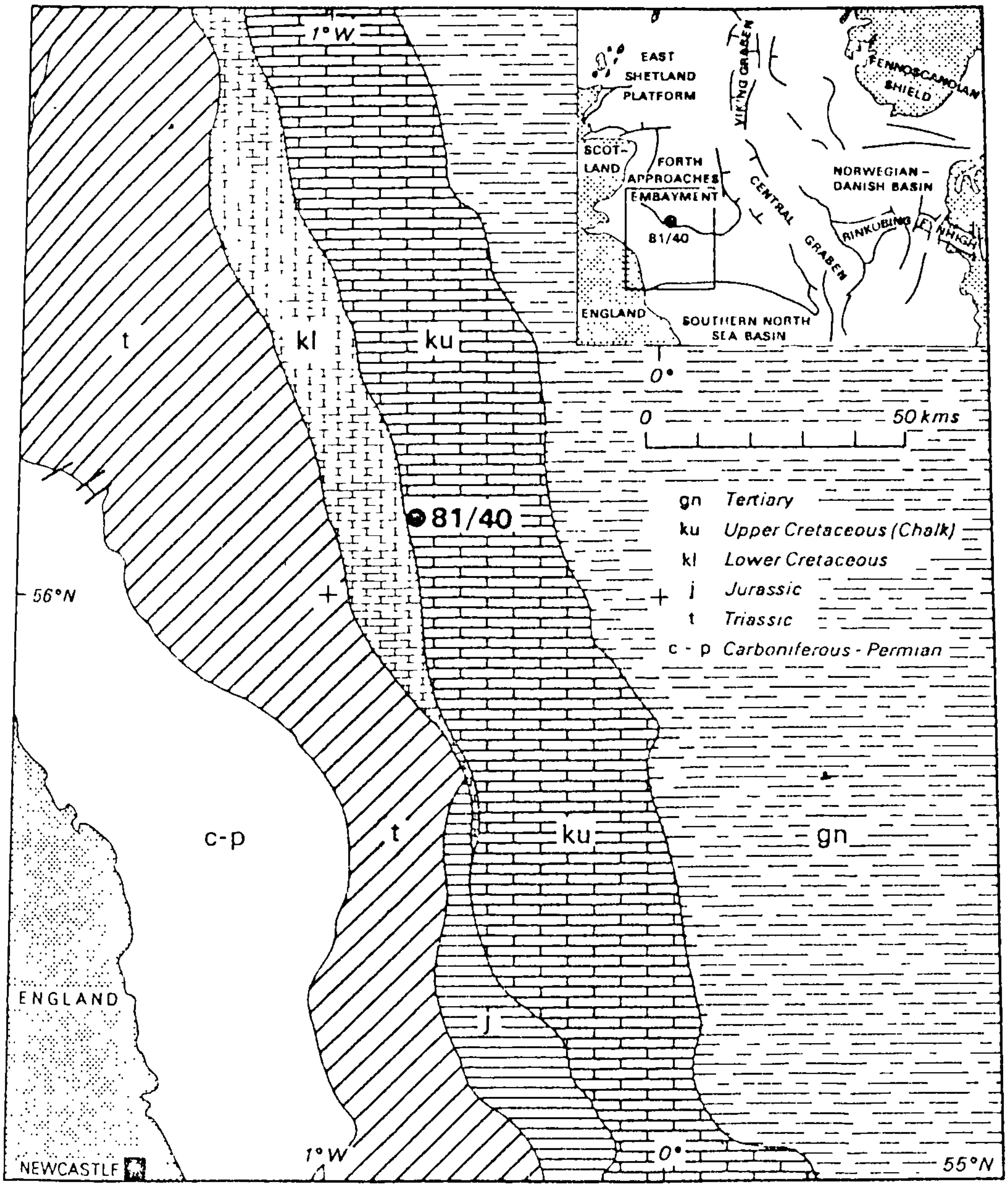


Figure 8.1 Location of borehole 81/40.

ostracoda enabling a preliminary biostratigraphy of the sequence to be described (Lott *et al.* 1985).

8.2. Lithostratigraphy of the sequence

8.2.1. Greenish grey mudstones (82.98–112.60m T D). ?Barremian to Middle Aptian.

This unit consists predominantly of greenish grey, strongly calcareous, burrow-mottled mudstones. These mudstones are only distinguishable from those of the overlying unit on their colour. Foraminiferal speckling of the core is a common feature and bioclastic debris is abundant. Small (up to 0.04m across), pale brown-rimmed phosphatic nodules commonly occur. Thin paler, hard, *Chondrites*-mottled marly limestone units are present at 94.22-96.84m and 98.07-99.94m, each showing an upward cyclic change from basal white marly limestones to pale greenish grey marls.

8.2.2. Red mudstones (71.77–82.98m). Middle to Late Aptian.

The unit consists predominantly of pale to moderate reddish brown (10R 4/5), strongly calcareous mudstones. The mudstones contain abundant bioclastic debris, including bivalve and belemnite fragments, giving the sediments a gritty texture. Foraminifera speckle the core and glauconite grains are abundant, giving a greenish tinge to the sediment. Pale yellow-brown, calcareous concretions occur at some levels. The base of the unit is marked by an abrupt colour change to pale greenish grey, calcareous mudstones; there is no associated erosion surface or significant lithological change.

8.2.3. Grey-brown mudstones (68.15–71.77m). Late Aptian to Early Albian.

The dominant lithology of this unit is uniform, grey-brown, calcareous burrow-mottled mudstones. There are 8 thin bentonites which range from pale greyish green to grey waxy clays, commonly with associated vivid green and red streaks and patches. The bentonites generally have sharp boundaries and

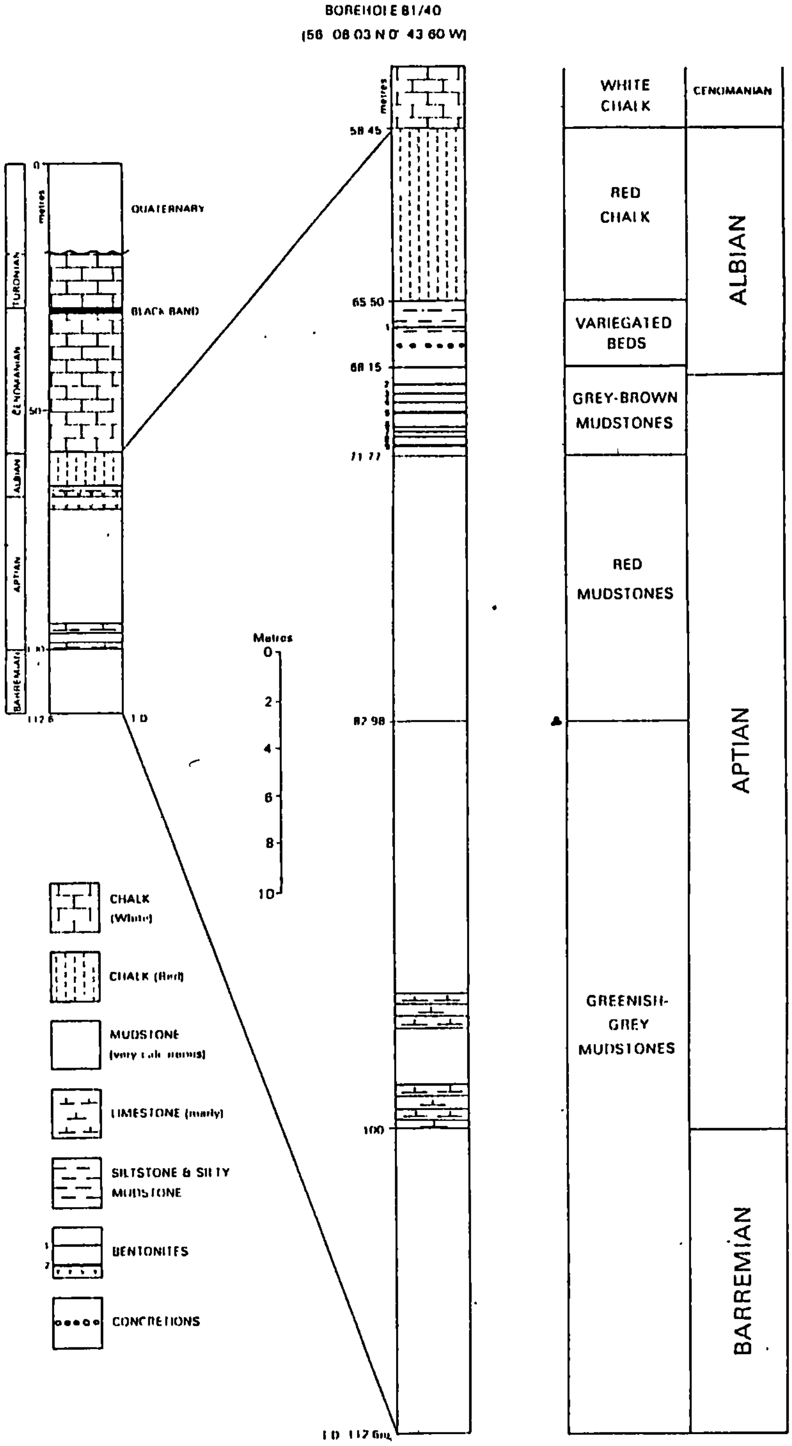


Figure 8.2 Summary log of the borehole.

in some cases a concretionary base. Grading in the bentonites is not apparent. They range from 20-160mm in thickness and some show traces of bioturbation. The interbedded grey-brown clays are commonly foraminifera speckled and contain rare shell debris. The base of the unit is marked by an abrupt colour change to the red mudstones of the underlying unit. The top of the unit is a strongly bioturbated erosion surface.

8.2.4. Variegated beds (65.50-68.15m). Early Albian.

The sediments of this unit show considerable variations in both colour and lithology. The upper part of the sequence consists of pale reddish brown (10R 4/5.3), non-calcareous siltstones, with waxy mudstone laminae and patches. Bioturbation commonly occurs, often in discrete bands. Colour variations range from yellow-brown to deep red, and there is interbanding of mudstones, siltstones and more rarely, fine sandstone. A single thin purple-red bentonite horizon is develop at 66.60 to 66.61m within this interbedded sequence. The interval from 67.04 to 67.54m shows a particularly distinctive development of variegated concretions, set in a muddy matrix, which pass up into finely colour-banded (yellow to dark red) silty clays. Beneath this concretionary layer softer, greenish grey, silty, micaceous clays are developed. The base of the unit is marked by a change to more uniform burrow-mottled clays.

8.2.5. Red chalk (58.45-65.50m). Middle Albian - Cenomanian.

The base of this unit is taken at a marked change from siltstones to red brown chalk, and the top at a comparatively abrupt colour change to off-white chalks of the overlying unit. Bioclastic debris, including bivalve and belemnite fragments, is abundant, giving the sediments a gritty texture. Burrow-mottling commonly occurs throughout the sequence, varying from large sub-vertical and horizontal burrows to a Chondrites type. Pale pink patches and off-white haloes are often associated with some of the larger burrows and an irregular banding of strongly and weakly bioturbated horizons may be developed. Thin bands of pale brown chalk nodules in a darker muddy matrix occur sporadically, together with sub-vertical, mud-filled fractures and thin dusky-red mudstone bands. Glauconite and pyrite speckling is particularly prominent at some levels.

8.2.6. White chalk (c.18.0–58.45m). Cenomanian to Turonian.

The unit comprises white to brownish white, argillaceous and nodular chalks. Flints are common in the chalk above the Black Band but are absent in the more argillaceous sequence beneath. Core recovery was in general poor owing to the comparatively soft nature of the chalk.

8.3. Conclusions

Borehole 81/40 was sited, using shallow seismic profiles, on gently eastward-dipping Cretaceous strata in the Forth Approaches Embayment. In consequence, the sequence cored in Borehole 81/40 should prove to be more complete and representative of the basinal areas than many commercial wells sited on positive anticlinal or fault controlled structures.

Early Cretaceous sedimentation in the North Sea Basin was characterised by the deposition of thick clay sequences which range in age from Ryazanian to Aptian and which are generally assigned to the **Speeton Clay Formation** of the **Cromer Knoll Group** (Rhys 1974; Deegan and Scull 1977). Deposition took place mostly in quiet-water marine environments producing monotonous clay sequences in which the major lithological variations are a result of subtle changes in carbonate content. These changes appear to reflect an increase or decrease in abundance (and diversity) of microfaunal and microfloral assemblages as the sea transgressed and regressed across the basin, improving or inhibiting circulation, and therefore oxygenation of the basin waters.

The oldest sediments encountered in borehole 81/40 are of Early Aptian to Barremian age. According to the ostracod faunas, the basal 12m of the greenish-grey mudstones are Barremian, whereas according to the foraminifera they are Early Aptian. It is not possible to resolve this discrepancy on the information obtained from this borehole alone. One possible explanation is that the borehole sequence is more complete than those of onshore north-west Europe, so that individual species could range beyond their known stratigraphical limits.

The upward incoming of coccolith-rich marly limestones at 99.94m (Dr A. W. Medd pers. comm. 1983), with abundant and diverse microfaunal assemblages, in undoubted Early Aptian sediments, provide a further indication of improving circulation in the basin as the transgression progressed. The occurrence of limestone developments is a characteristic feature of the Early Aptian of the North Sea Basin (Rawson and Riley 1982). By Mid - Late Aptian times, a renewed marine influx into the basin is indicated by the sudden proliferation of the planktonic foraminifer Hedbergella infracretacea (Lott et al. 1985). In the borehole sequence, it is notable that the incoming of this planktonic species is also coincident with the change to reddened calcareous mudstone lithologies. The abrupt colour change and reddening of both the Late Aptian mudstones and the Mid Albian - Early Cenomanian chalk is widespread throughout the North Sea area, and occurs not only in condensed sequences over the more positive areas but also in sequences between the highs. In both instances the reddening appears to be associated with transgressive phases, suggesting that increased oxygenation of the bottom waters may in part be responsible for the retention of an original red coloration of the sediments and indicating a shallow-water depositional environment (Jeans 1980; Gallois and Morter 1982).

Conformably overlying the red mudstones, the latest Aptian sediments in

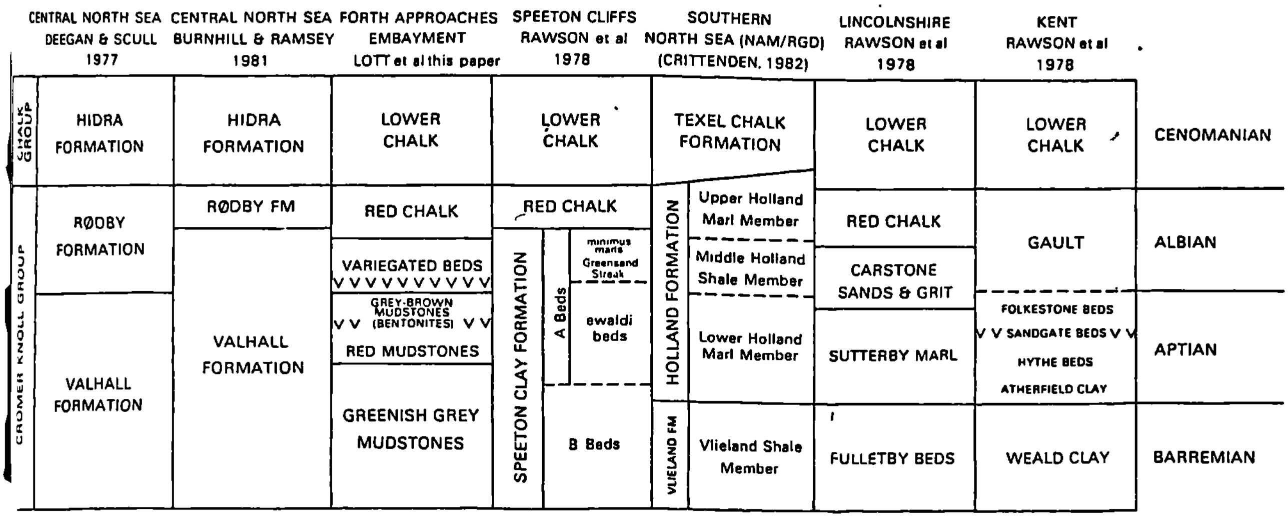


Figure 8.3 The lithostratigraphy of the Mid-Cretaceous of eastern England and the North Sea.

the borehole comprise brown-grey mudstones with interbedded bentonites, the volcanic origin of which is indicated by the presence of sanidine feldspar and biotite as common detrital constituent grains. The mudstones have yielded microfaunal asemblages which suggest a P.nutfieldiensis Zone (Late Aptian) age. Widespread volcanic activity is apparent at this level in the Late Aptian throughout much of the north-west European area, and volcanic sediments have been described from this zone both in southern England (Sandgate Beds at Folkestone; Jeans et al. 1982) and in Germany (Sarstedt and Thiede; Zimmerle 1979) (Figure 8.4). It is interesting to note that at Speeton cliffs bentonitic horizons have not yet been describe from the Aptian-Albian sequences. However, it is worth noting that the common association of these bentonitic horizons with vivid green 'glauconitic' streaks and patches in both this borehole and in the German succession may be mirrored at Speeton, where green glauconitic bands and streaks have also been described from the clay sequence immediately below the Late Albian Red Chalk (Lamplugh 1899; Kaye 1964). Poor exposure of this part of the sequence at Speeton cliffs at present precludes confirmation of bentonitic bands at this level.

The source of the volcanic material which is largely acidic to intermediate in composition, has been suggested as either a site in the southern North Sea or in the western English Channel and South West Approaches (Jeans et al. 1982). These Late Aptian bentonites are the product of one of two important phases of Lower Cretaceous volcanic activity in the north-west European area, the other occurring in the Ryazanian (Figure 8.3) (Knox and Fletcher 1978; Zimmerle 1979; Chapter 7) and coinciding with increasing tectonism at the plate margins to the west of Britain, associated with the opening of the Rockall Trough and rotation of the Iberian peninsula (Anderton et al. 1979).

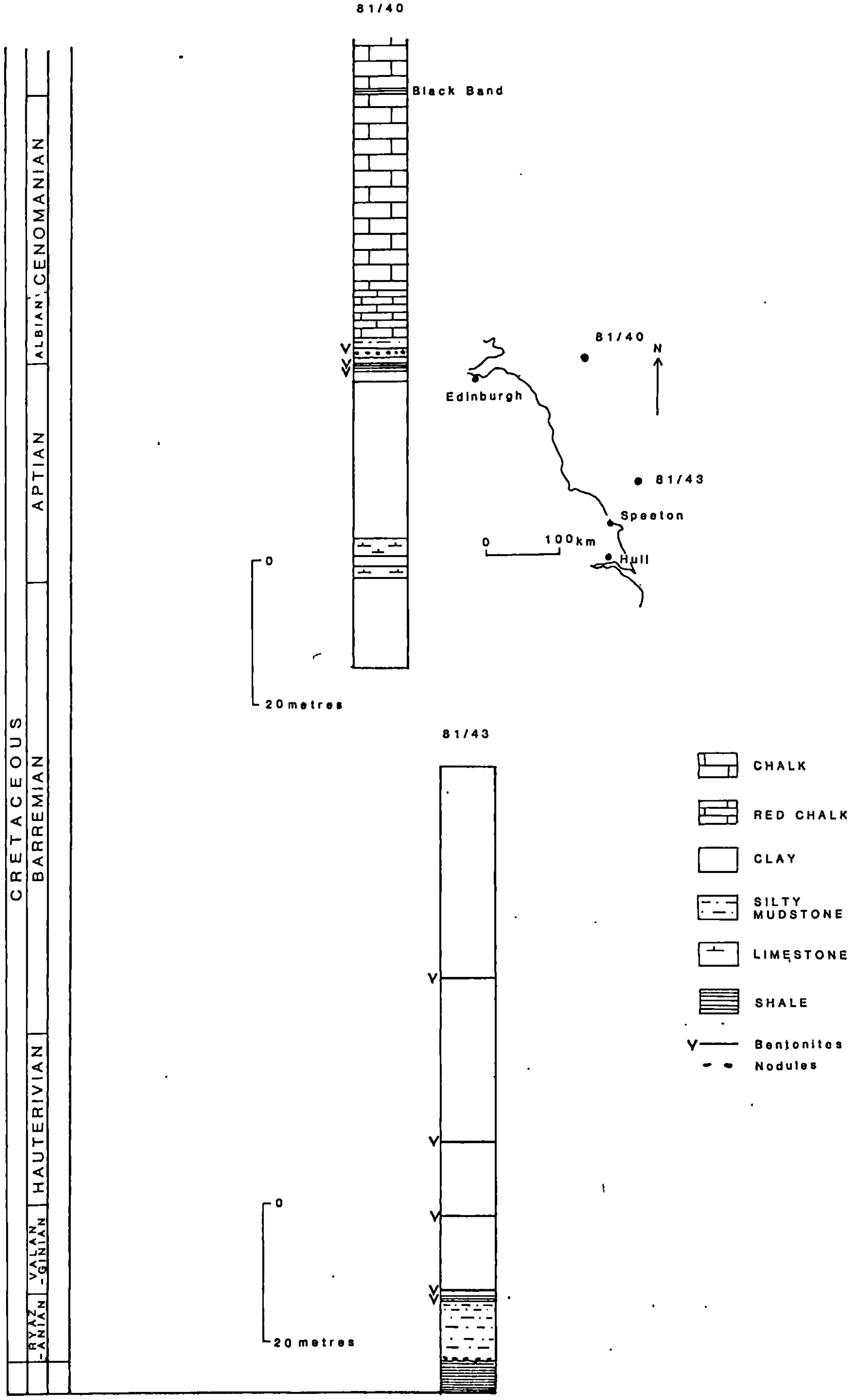


Figure 8.4 The distribution of bentonites in the Mid and Early Cretaceous successions of the North Sea.

On foraminiferal grounds, the Aptian / Albian boundary in the borehole sequence lies just below the marked unconformity that separates the grey-brown mudstones from the overlying variegated beds. The topmost part of the grey-brown mudstone unit is, however, strongly bioturbated and it is certainly possible that the erosion surface may represent the Aptian / Albian stage boundary in the borehole, and that reworking during the Early Albian transgression is responsible for any discrepancy between the biostratigraphical and lithostratigraphical boundaries.

This Early Albian transgression, characterised initially by extremely impoverished microfaunas and floras, is well documented in the European basin (Price 1977). In the borehole sequence, the Early Albian interval comprises a thin but extremely distinctive sequence of variegated clays and silts which contain a microfauna restricted to agglutinating foraminifera; no ostracods or coccoliths have been recorded. Within this variegated sequence a single bentonitic horizon suggests a continuation of sporadic volcanic activity over the basin into the Early Albian. The transition to the overlying red chalk sediments is associated with the basinwide Mid-Albian transgression.

The 'red chalk' in the borehole ranges from Mid Albian to Early Cenomanian in age. The sequence does not show the marked nodular development characteristic of much of the red chalk sequence at outcrop in Yorkshire and Lincolnshire and comprises largely uniform red chalk sediments. The transition to white chalk sedimentation occurs during the Early Cenomanian with the development of argillaceous white Chalk sediments. A thin black clay, the Black Band, forms a widespread marker close to the Cenomanian - Turonian boundary throughout much of the North Sea Basin (Hart and Bigg 1981) before a return to more normal white chalk sedimentation during the Turonian.

CHAPTER 9

The geology of the California Sheet (54° N 00°, quadrants 42 and 43) in the Southern North Sea Basin.

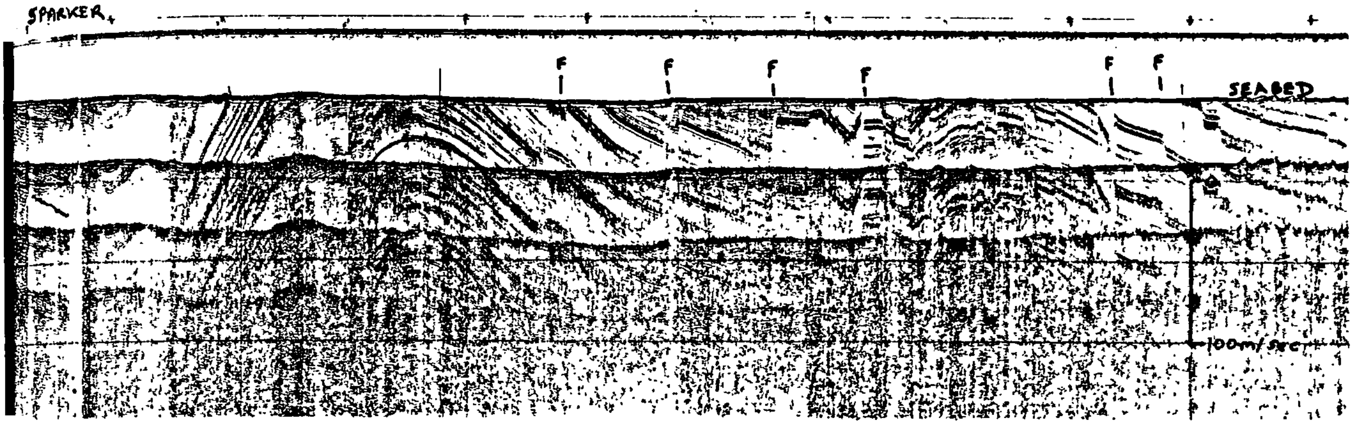
The geology of the California Sheet (54 N 00 , quadrants 42 and 43) southern North Sea.

9.1. Introduction

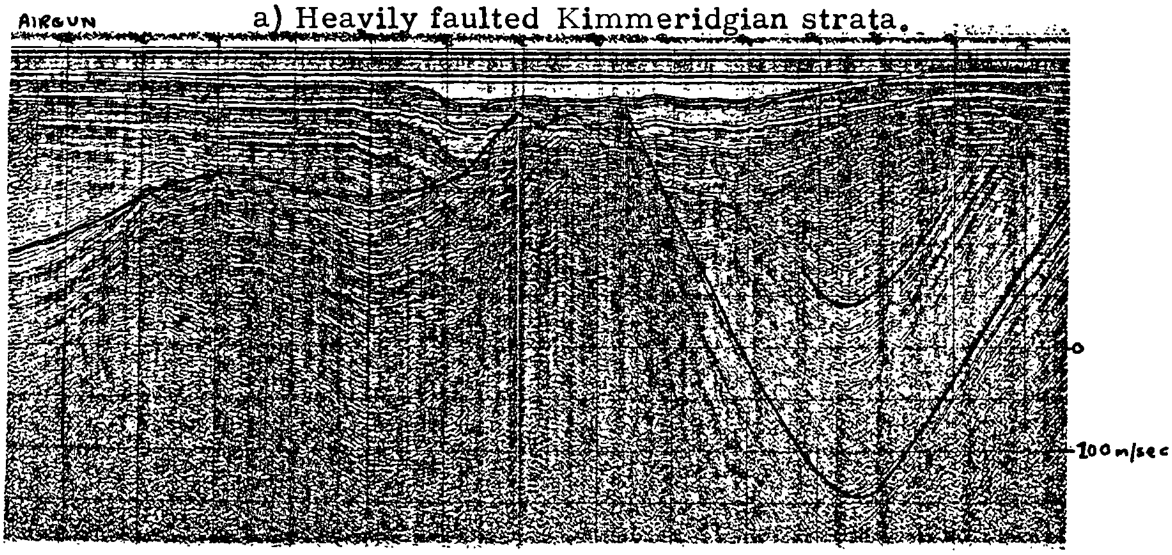
Investigations by the British Geological Survey (B.G.S.) of the seabed geology of the California Sheet (54^{o}- 55^{o} N, 0^{o}- 02^{o} E) began early in 1981 with shallow seismic surveys of the area. In total approximately 4320 km of seismic were collected along east-west and north-south traverses with a grid spacing of about 5 km (Enclosure 2). Seismic equipment used included a 1 kilojoule sparker and 5 or 10 cu.inch airguns, high resolution pinger and boomer and sidescan sonar. Following these seismic surveys a series of seabed sampling and shallow drilling surveys were carried out to improve the interpretation of the geophysical data. In total 177 bedrock samples were collected and 10 shallow cored boreholes drilled within the sheet area.

Prior to this work by the BGS the geological outlines of the area and its broad relationship to the main part of the Southern North Sea Basin were established by Kent (1967) and Dingle (1971). The sheet name California is derived, because of the sparsity of named seabed features in the area, from an important fishing ground in the south-west part of the sheet and is a result of the practice of local fishermen in the early 19th century of naming particularly rich fishing grounds after contemporary gold strike areas e.g Klondyke. The California sheet, which covers licence

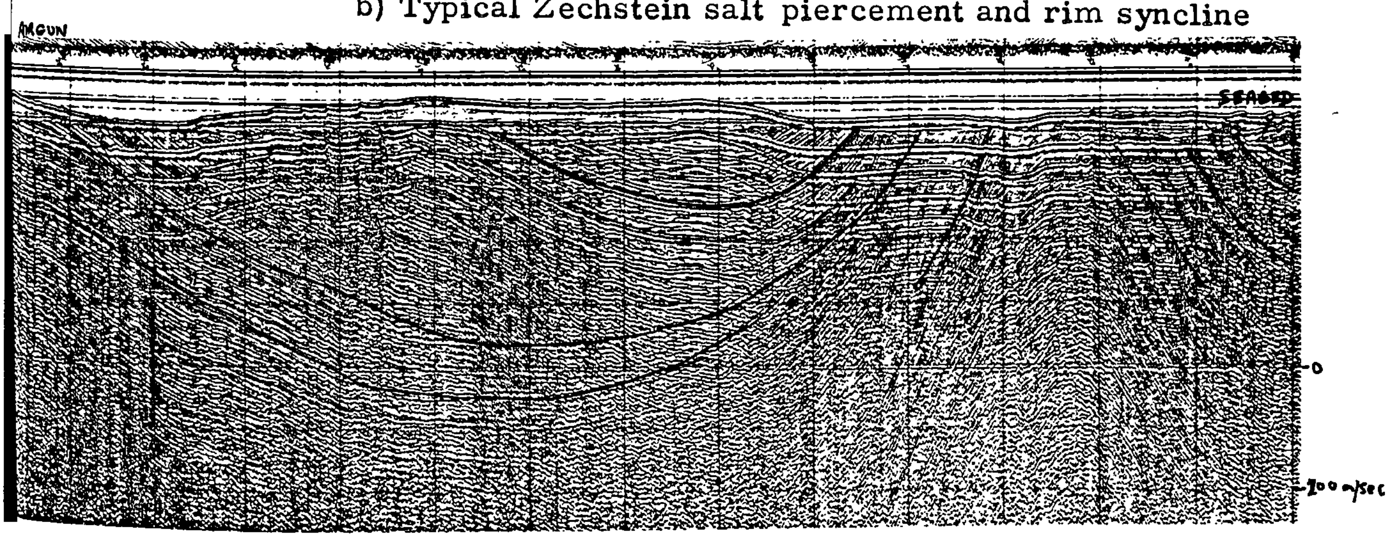
Figure 9.1 Seismic sections from the California Sheet area showing the effects of salt tectonics on the structure of the area



a) Heavily faulted Kimmeridgian strata.



b) Typical Zechstein salt piercement and rim syncline



c) Rim syncline with thick well-bedded Lower Jurassic and Cretaceous fill quadrants 42 and 43, occupies the northern margin of the Southern North Sea Basin proper, which is bounded at its northern margin by the structurally positive Mid-North Sea - Rinkobing-Fyn High. Consequently, many of the Mesozoic, Tertiary and Quaternary units thin over the northern part of the sheet as the high is approached. This northward thinning is further complicated by the effects of salt tectonics. The thick Zechstein (Late Permian) salts have shown considerable mobility since the Middle Triassic due to a combination of burial depth and tectonic stress. The resulting swells and troughs, which have influenced both sedimentation patterns and structural development in the area, have together produced a seabed outcrop pattern of considerable complexity.

Commercial drilling for hydrocarbons commenced in the area in 1966 and early results were disappointing, judged in the light of the considerable success of the drilling further to the south. The Rotliegendes (Early Permian) dune sandstones, the primary gas reservoir in the main basin to the south, show a transition to non-prospective siltstone and mudstone facies within the sheet area. Exploration (1983 onwards) has resumed in the area since the economic conditions are now making smaller gas prospects in the fluvial sandstones of the Triassic (Bunter Sandstone Formation) increasingly atractive. To date five small gasfields are being developed: Esmond, Forbes, Gordon, Cleeton and Ravenspurn. The geological details from most of the early wells drilled in the area have now been released from confidentiality by the Department of Energy and these data have been used extensively in the preparation of this map to help determine the deep geological structure and lithostratigraphy of the area and to tie in reflectors on the seismic profiles.

9.2. Structure

The structure of the California sheet area is dominated by a series of north-west trending folds. Erosion along the axial areas of these structures has produced a complex outcrop pattern on the western part of the sheet as successively older strata are exposed as concentric shells until Permo-Triassic sediments are revealed at their core. Commercial deep drilling and seabed sampling along the axes of these folds has shown that these undulating structures have thick Zechstein salt (up to 1500m) as a core.

Faulting is extremely widespread in the sheet area. The shallow seismic profiles indicate quite a high density of minor faults but the widely spaced nature of the seismic grid precludes a detailed analysis of the fault trends. A zone of major faulting is apparent running north to south through the sheet area and has been termed the **Central Fracture** Zone(Enclosure 1). This zone is a major listric fracture downthrowing to the east, and appears to mark the western limit of salt movement (Enclosure 1). Its southern limit is coincident with the north-west trending Dowsing Fault Zone at the western margin of the Sole Pit Trough to the south (Enclosure 1). To the west of this zone the Zechstein salt sequence is thinner and structures within the Mesozoic show a less rigid north-west trend. West of the Central Fracture Jurassic and Cretaceous sequences are not well preserved and no Tertiary sediments have so far been proved during sampling. Seismic evidence suggests, however, that there is a possibility that Tertiary strata may occur in the south west corner of the sheet area in the rim synclines of a large salt structure.

9.3. Geological History.

The Southern North Sea Basin has a complex history of long periods of subsidence punctuated by periods of uplift and inversion. The most recent consensus of views on the development of the North Sea basin (e.g. Ziegler 1981; Donato and Tully 1981; Leeder 1983) suggest that it was iniated during the Early Permian by slow subsidence north and south of the already established Mid-North Sea High. Subsequently a tensional phase of rifting and stretching of the lithosphere led to the formation of the major graben systems which dominate the North Sea basin north of the Mid-North sea High. A phase of slow subsidence followed through Triassic and Jurassic times until the Early Cretaceous when localised uplift and inversion began to affect the Southern North Sea Basin, producing the Cleveland and Sole Pit Inversion structures. Subsequent release of this tension then led to cooling and flexuring of the lithosphere and more general subsidence throughout the North Sea Basin in the Late Cretaceous and Tertiary.

9.4. Pre-Permian Basement

Little information is available regarding the pre-Permian geology of the basin within the sheet area. This is largely because the initial deep drilling proved that the main gas prospect in the area, the Rotliegendes sandstones, were either thin or showed a change into a non-prospective fine grained clastic sequences. Later wells, therefore, tended to terminate as soon as Late Permian (Zechstein) sediments were penetrated. A few commercial wells, however, have proved that Carboniferous sediments underlie much of the sheet area (Enclosure 1; Eames 1975). They range from Lower Carboniferous limestones to Westphalian coal measure sequences; the latter are the major source rock for the gas found in the overlying Bunter Sandstone Formation.

9.5. Rotliegendes Group (Early Permian)

The sediments of the Rotliegendes Group in the sheet area show a transition northwards from aeolian dune sand sequences to muddy, wadi-type saliferous mudstones and siltstones. The northern margin of the Early Permian basin lay within the sheet area and shows a thin discontinuous sandy sequence often lying directly on eroded pre-Permian basement rocks. The

Mid-North Sea - Rinkobing-Fyn High divided this southern Permian basin from a similar subsiding trough to the north (Glennie 1984).

9.6. Zechstein (Late Permian)

Late Permian sedimentation in the North Sea area, both north and south of the Mid-North Sea High, saw the establishment of shallow highly saline seas in the basin. Thick cyclic sequences of reefal carbonates and sabkha type evaporites were deposited in the basin (Taylor and Colter 1975). This Zechstein basin extended eastwards into Germany where the sequence has been divided into 5 carbonate/evaporite cycles of sedimentation (Z1-Z5). The California sheet lies on the north-west margin of the basin, carbonate reef facies are well developed and 4 of the major cycles (Z1-Z4) have been recognised in the boreholes drilled (Enclosure 1). These Zechstein sequences include considerable thicknesses of salt and it is the mobility of these salt units under tectonic stress that has allowed the development of a range of spectacular salt diapirs and piercements across the basin (Figure 9.1; Trusheim 1960). The mechanism which triggered these salt movements is still not fully resolved but is likely to be a combination of basement faulting and 'gravitational creep' over the original basement topography. The initial phase of movement is considered to be associated with Middle Triassic tectonics, post-dating the deposition of the fluvial Bunter Sandstone Formation, which is the oldest unit to show erosional thinning over the crests of some of the salt structures. Once initiated, the salt movement continued spasmodically, reactivation occurring probably in association with tectonic episodes which periodically affected the basin. Salt withdrawal around the margins of the salt swells allowed the development of rim-synclinal structures, within which later thick syn-depositional sediment piles accumulated. These sediment traps themselves contributed to further salt movement as the overburden on the salt increased. The effects of salt movement decrease both northwards and westwards over the sheet area as a consequence of the thinning of the Zechstein sequence as a whole onto the Mid-North Sea High and into the Cleveland Basin where Zechstein salt sequences show no significant diapiric phase.

9.7. Triassic

Triassic sediments subcrop most of the sheet area but only occur at outcrop as isolated inliers along the axes of some of the larger salt swells. This red bed sequence may be divided into a lower shale unit - the **Bunter Shale Formation,** a middle fluvial sandstone unit - the **Bunter** Sandstone Formation (these two units forming the **Bacton Group**), and an upper saliferous shale unit (the **Haisborough Group**). Each of these units is preserved in wells drilled within the sheet area (Enclosure 1). The units thin gradually northwards onto the Mid-North Sea High but overall the Triassic sediments are remarkably consistent in both lithology and thickness. Thin saliferous beds are commonly well developed in the Triassic succession to the south but, with the exception of the Rot Salt Member, they die out northwards and westwards across the sheet area. The gradual amelioration of the climate at the end of Triassic times is reflected in the deposition of marginal marine shales and interbedded sandstones of the **Winterton Formation.** The sediments of the Winterton Formation have only been proved at outcrop around the flanks of the Scarborough Dome. BGS borehole 81/44 (Figure 2.2) cored a 13.85m thick sequence through the Winterton Formation on the flanks of this structure. The sequence cored ranged from pale greenish-grey dolomitic marls, with a blocky to brittle fracture, (topmost part of the Haisborough Group) at the base, into thinly interbedded white fine-grained, anhydrite cemented sandstones and black mudstones, with a rich macrofauna of pyritised bivalves, characteristic of the Westbury Formation of the Penarth Group (Dr. Ivimey-Cook 1984 pers comm.). The topmost unit was a dark grey mudstone of probable Lower Jurassic age though no diagnostic macro- or microfaunas were obtained. The stratigraphy and petrography of this sequence and of the Winterton Formation in general is discussed more fully in Chapter 2 of this thesis.

9.8. Jurassic

The Jurassic succession in the California sheet ranges from Hettangian to Kimmeridgian in age and representatives from most of the Jurassic stages have been sampled, either in cored boreholes or by seabed sampling techniques. (Enclosure 1; Appendix 3). The Jurassic succession outcrops at or near seabed over a north-west trending area across the south-west part of the sheet. This succession is contiguous with that of the Sole Pit Trough, but was not as severly affected by the phase of inversion and erosion of the basin which was largely took place in Early Cretaceous times.

9.8.1. Lower Jurassic (Lias Group)

The Lower Jurassic sediments in the sheet area range from Hettangian to Early Toarcian in age and reach up to c.500m in thickness (Chapter 3). The sequence comprises typically, dark grey to grey calcareous, silty, mudstones interbedded with grey, argillaceous, limestones. In the shallow seismic profiles the Lower Jurassic sequences typically show a gently dipping, well-bedded sequence which is folded into a series of minor anticlines and synclines (Figure 9.3). The base of the sequence is marked by a change to a less regular seismic character, but no basal unconformity with the Triassic sequence is apparent. The higher amplitude reflectors commonly seen in the sequence are probably related to carbonate rich beds. The most prominent is formed by the Staithes / Cleveland Ironstone Formations. This unit, as in the onshore area, forms a distinctive

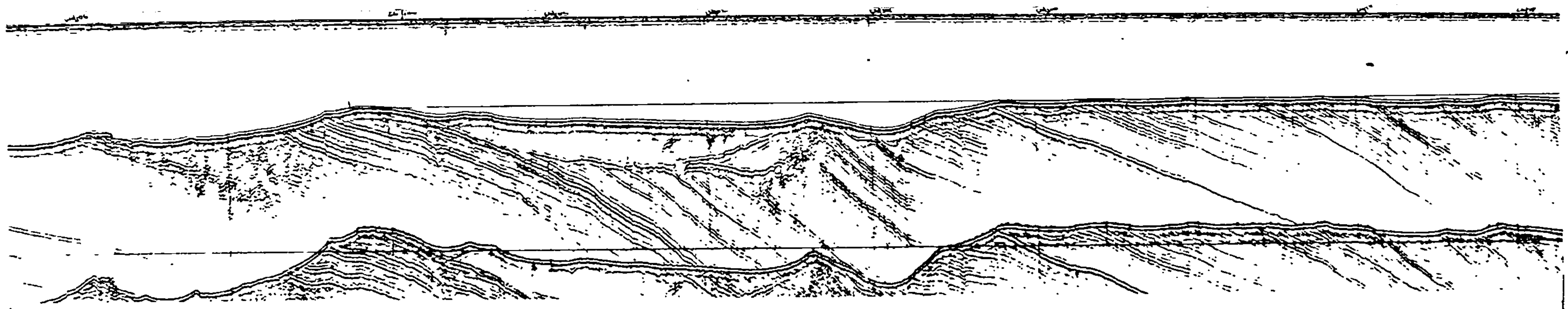
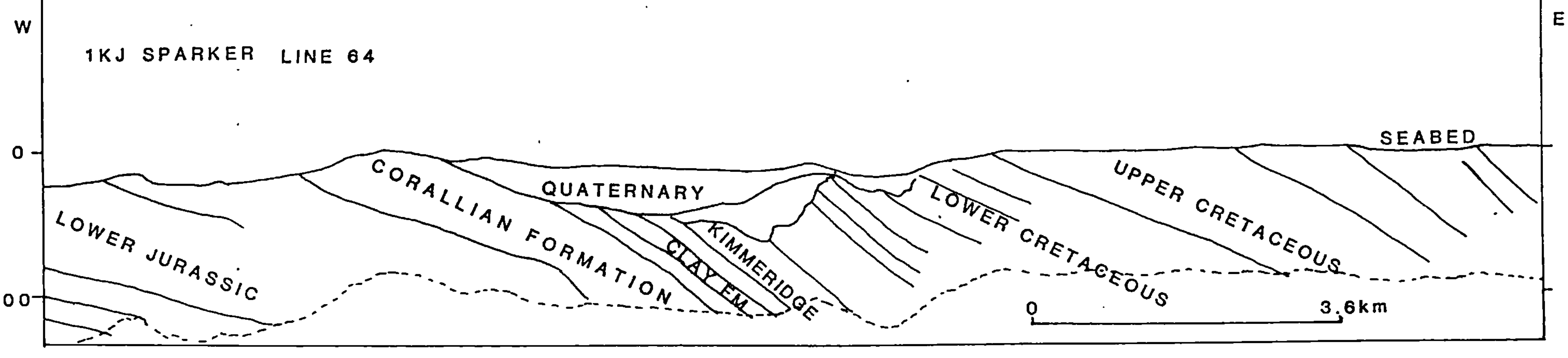


Figure 9.2 Sparker profile showing a transect across the Jurassic outcrop.



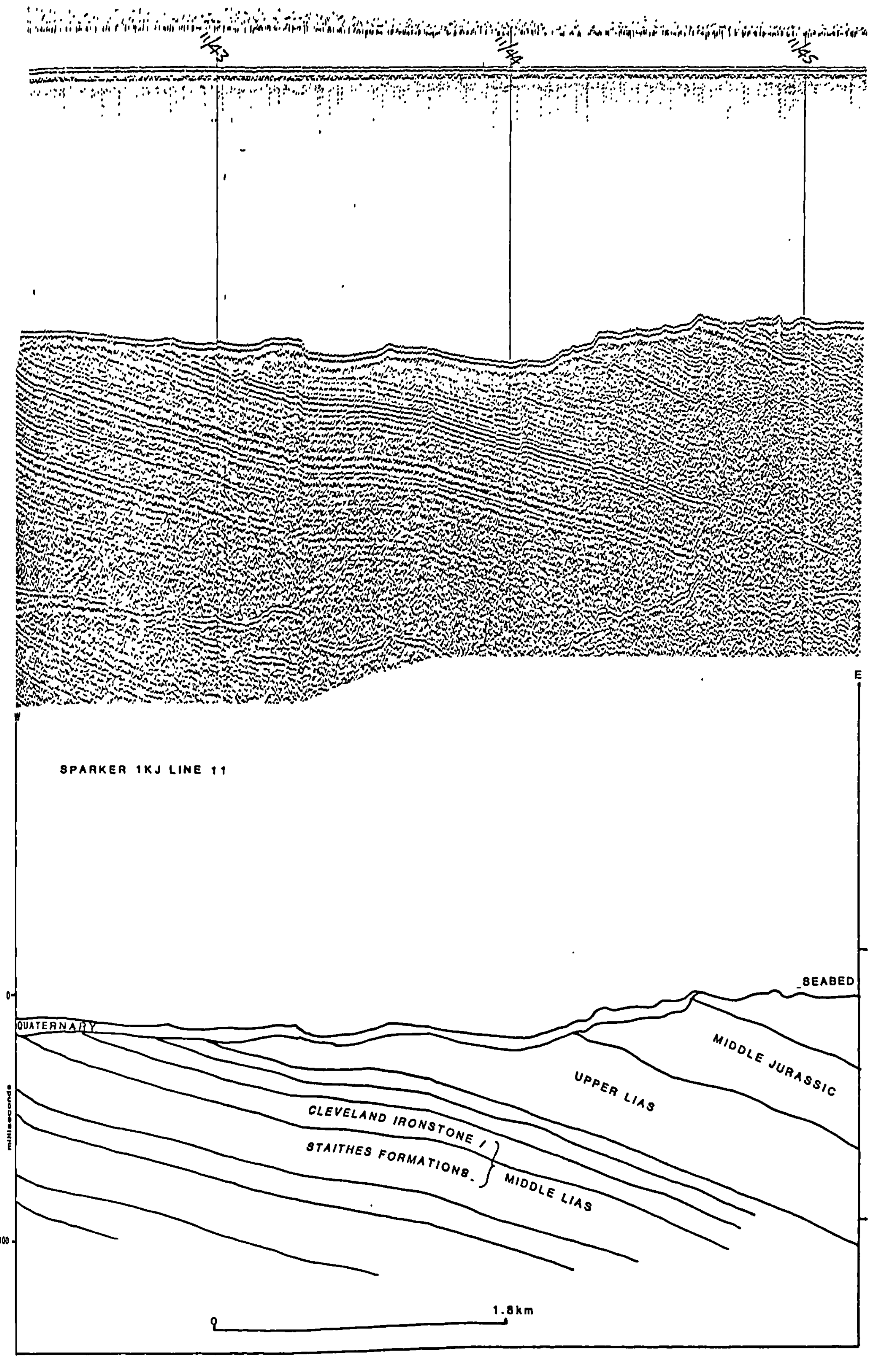


Figure 9.3 Sparker profile across the Middle/Upper Lias boundary showing the well-bedded nature of the Lower Jurassic.

topographic ridge on the seabed and has been mapped within the sheet area (Enclosure 1, Figure 9.3). No samples were obtained from the unit itself because of the hard nature of the lithologies involved, but its age was confirmed by sampling the the softer mudstones on either side of the feature. This Middle Lias interval is also a prominent marker on the downhole geophysical logs from commercial wells drilled through the sequence (Chapter 4). The upper boundary of the Lower Jurassic succession is marked by an obvious change from the well bedded Lower Jurassic into the more chaotic seismic character of the Middle Jurassic succession. This change allows the mapping of the basal boundary of the Middle Jurassic over the sheet area with some confidence. The Lower / Middle Jurassic boundary has been cored in BGS borehole 81/42 (Figure 9.4). The borehole proved an 11.00m sequence of carbonaceous clays and thin sandstones with a thin spherulitic siderite unit and a thin sideritic ironstone, resting on dark-grey, non-calcareous clay, which in turn rests on dark grey,silty mudstones with thin bituminous horizons (11.00m thick). This lowermost calcareous mudstone unit yielded an abundant macrofauna of Early Toarcian age (Dr. Ivimey-Cook pers. comm. 1985).

The phase of pre-Aalenian tectonism and erosion, well documented onshore in eastern England (Hemingway 1974), is evident in the offshore area from seismic and well data which both confirm the variable thickness of the Upper Lias sediments which overlie the Staithes / Cleveland Ironstone Formation. However, no clear angular unconformity is recognised between the Middle and Lower Jurassic sequences seen on the seismic profiles.

9.8.2. Middle Jurassic (Bajocian-Callovian, West Sole Group)

The Middle Jurassic sediments in the sheet area reach a maximum thickness of c.150m in the rim synclines in the south of the sheet, but

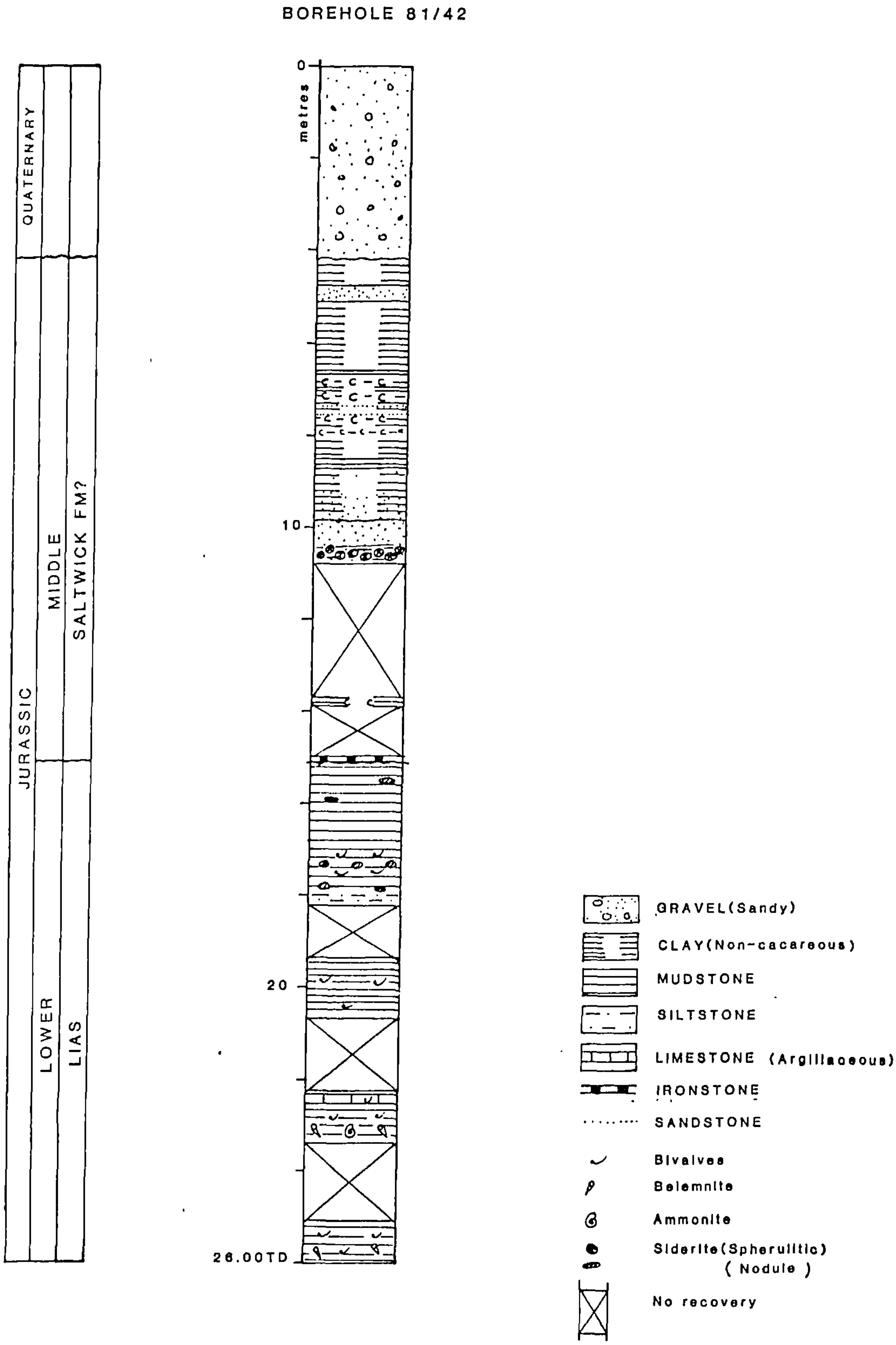


Figure 9.4 Summary log of borehole 81/42.

from borehole and seismic evidence thin markedly northwards onto the Mid-North Sea High. The Middle Jurassic outcrop in the sheet area is generally very narrow and consequently few samples were obtained from the sequence. The boundaries of the unit were mapped using the seismic character of the unit, which comprises a distinctly chaotic series of reflectors when compared with the well bedded nature of the underlying Lower Jurassic sequence and overlying well-bedded Upper Jurassic strata. The few samples obtained from the sequence largely comprise lithologies similar to the non-marine sequences of the Cleveland Basin (Appendix 3). BGS borehole 81/42 as discussed above (Figure 9.4) cored an 11 m sequence of non-marine Middle Jurassic sediments ?Saltwick Formation, resting on Liassic strata. In this borehole there was no evidence of the basal Middle Jurassic marine Dogger Formation. However, seabed samples which were obtained at other localities close to this boundary comprised green-grey chamositic, oolitic ironstones similar in character to the Dogger Formation of the Cleveland Basin (Appendix 3). Non-marine carbonaceous sandstones and interlaminated mudstones and siltstones of Middle Jurassic age were also sampled. The Middle Jurassic succession has been drilled in only a few commercial wells in the sheet area and only cuttings material is available. The stratigraphic delimitation of the Middle / Upper Jurassic boundary is in general the most problematical in the Southern North Sea Basin (see Chapter 3). In the sheet area this boundary, which lies within an almost continuous sandy succession, was defined using seabed sample data and by reference to the overlying Corallian Limestone unit which forms one of the most widely mappable seismic horizons within the Jurassic (Figure 9.6). A number of seabed samples and short cores of Callovian sequences were drilled (Figure 9.5). The Callovian-Lower Oxfordian interval comprises marine sandstone sequences ranging from clean grey, bioclastic sandstones

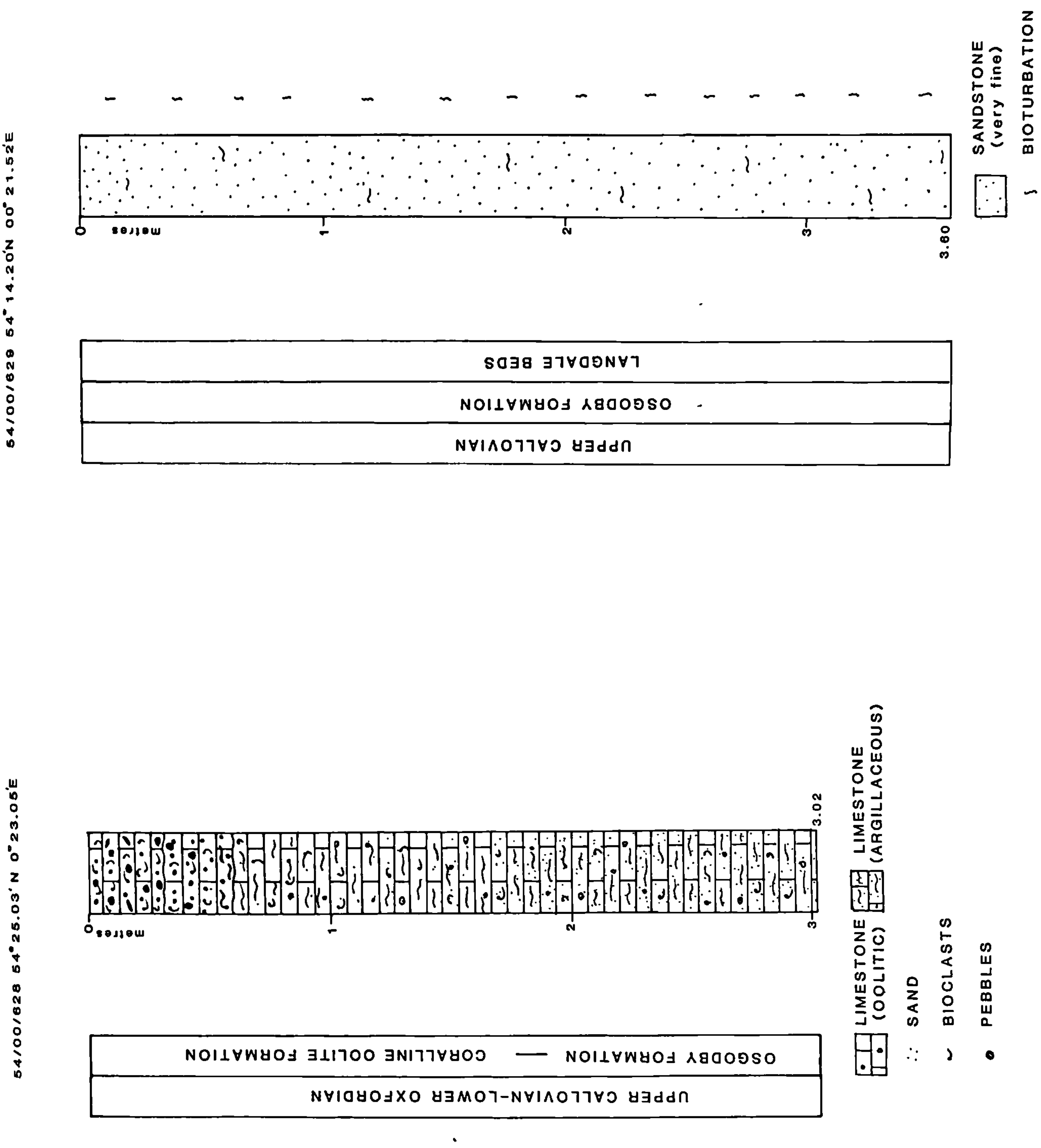


Figure 9.5 Summary log of Callovian - Lower Oxfordian sandstone rockdrill cores.

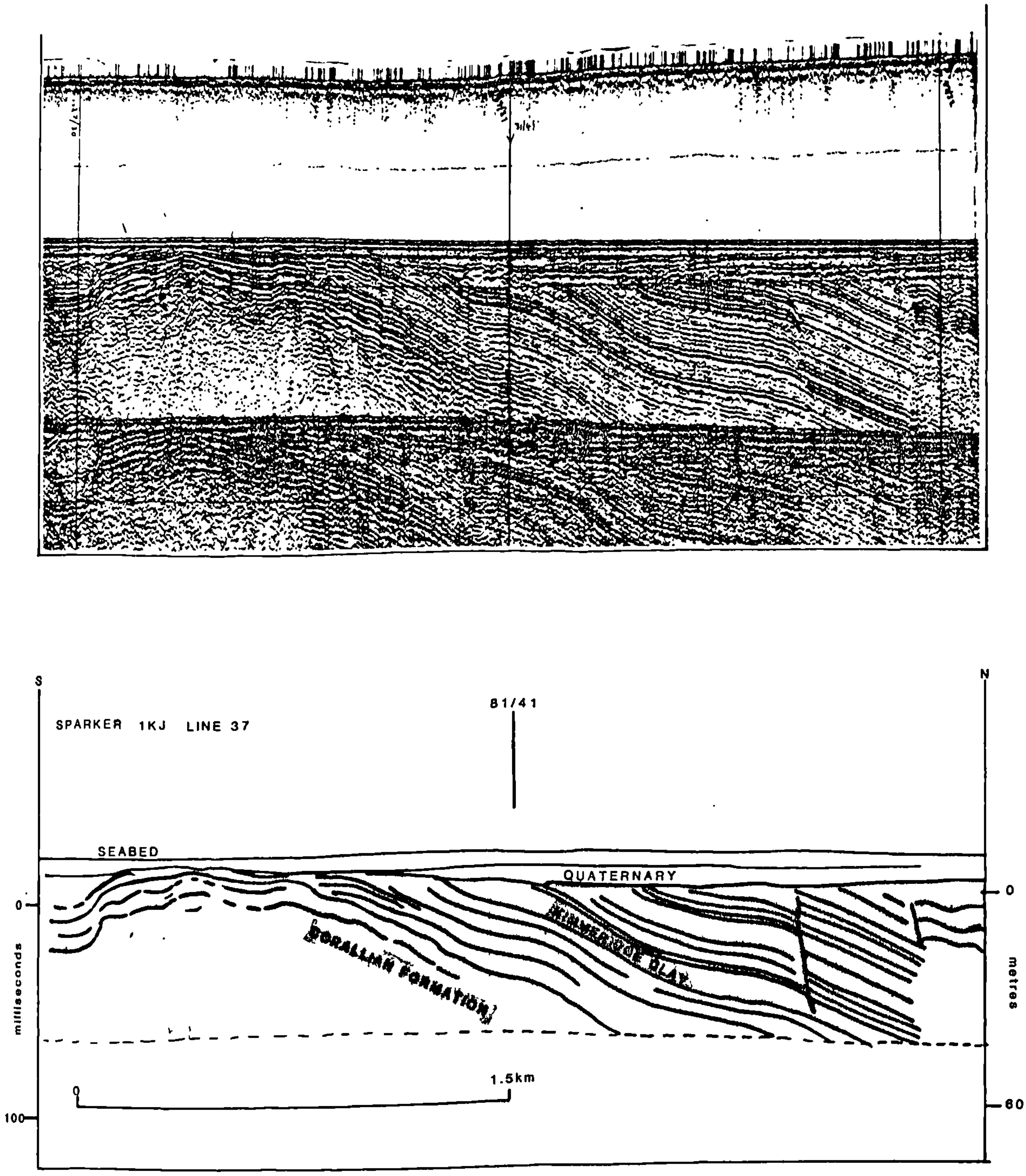


Figure 9.6 Sparker profile of Corallian and Kimmeridge Clay Formations taken through borehole site 81/41.

to more muddy, greenish grey, oolitic and chamositic sandstones. The chamositic sandstone are lithologically similar to the Hackness Rock of the Cleveland Basin and as far as can be ascertained, from micropalaeontological evidence, lie at about the same stratigraphic level.

9.8.3. Upper Jurassic (Oxfordian to Kimmeridgian, Humber Group

Upper Jurassic sediments outcrop extensively across the sheet area and have been cored in a number of shallow boreholes and in many seabed samples (Enclosure 1). The Upper Jurassic sequence can be divided seismically into two distinct units. A lower interval characterised by a prominent series of high amplitude seismic reflectors and forming a topographic ridge at seabed; this unit is composed of the cemented sands and limestones of the Lower **Calcareous Grit and Corallian Limestone Formations.** An upper unit of seismically well bedded character which is composed of the well bedded shales and thin cementstones of the **Kimmeridge Clay Formation** (Figure 9.6). This latter formation includes thin representatives of the sands and mudstones of the Upper Calcareous Grit and Ampthill Clay. Sample data indicates that the Corallian limestones are predominantly pale grey to creamy brown oolitic and bioclastic limestones (BGS boreholes 81/47, 82/22) resting, in the thicker sequences at least, on variably cemented, cherty sandstones with sponge spicules (<u>Rhaxella</u> sp.) of the Lower Calcareous Grit Formation.

An almost complete sequence of Kimmeridgian strata has been proved, within the sheet area, from both borehole and sample data (BGS boreholes 81/43, 81/46, 81/47, Chapter 6). The top of the Kimmeridge Clay Formation is marked by a slight angular unconformity with the overlying Lower Cretaceous Speeton Clay Formation (Figure 9.7).

9.9. Cretaceous

9.9.1. Lower Cretaceous (Ryazanian to Albian, Cromer Knoll Group)

Lower Cretaceous sediments in the sheet area comprise the calcareous and thin non-calcareous shales of the Speeton Clay Formation (Figure 9.8).

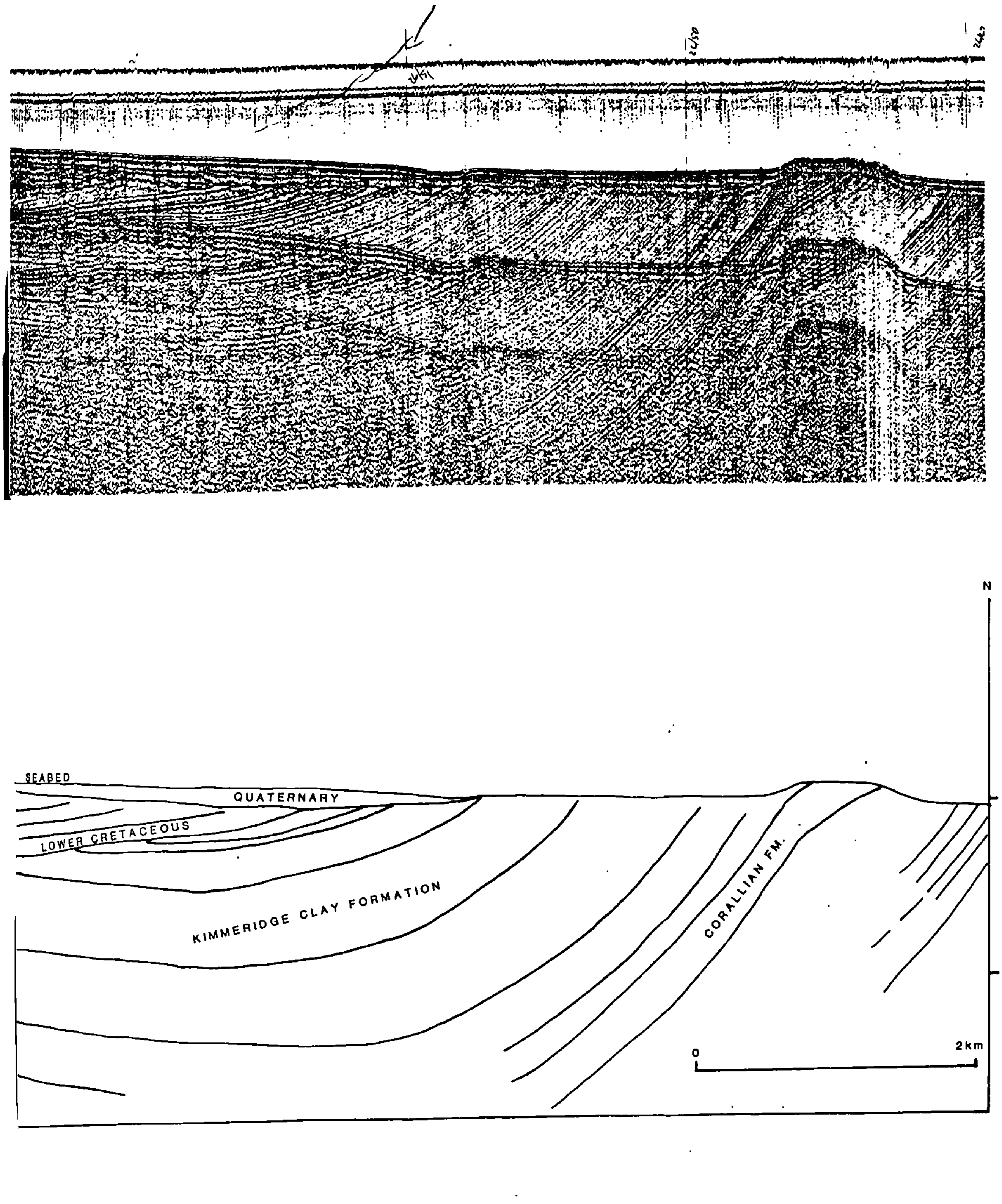


Figure 9.7 Sparker profile showing the Kimmeridge/Speeton Clay unconformity c.10km east of Flamborough Head.

Of particular interest is the development at various horizons of thin volcanic bentonites (Figure 8.3). The Speeton Clay reaches its greatest development, c.430m, in the south west part of the sheet and thins northwards onto the Mid-North Sea High. Local thickening of the sequence, associated with faulting, occurs within the sheet area e.g. Well 42/13-1, c.230m. The lower part of the succession has been cored in BGS borehole 81/43 (Figure 9.8) (Ryazanian to Barremian), and a detailed description of the sequence is included in Chapter 7 of this thesis. The upper part of the Speeton Clay Formation (Barremian to Albian) is known only from commercial borehole data. An examination of commercial well data from the upper part of the Speeton Clay Formation suggests the succession may be closely comparable with the sequence drilled, to the north of the sheet area, in BGS borehole 81/40 (Lott et al 1985; Chapter 8). From cuttings obtained from wells that have drilled a more expanded sequence (42/13-1, 43/15-1) a broad subdivision downwards from a red Chalk unit, through a high gamma / low velocity grey-brown mudstone unit (possibly equivalent to the Late Aptian/Early Albian bentonitic mudstones in borehole 81/40; Chapter 8), into a second red chalky marl unit overlying greenish grey marls with thin limestone intervals.

Within the sheet area the Speeton Clay outcrop is concealed beneath a cover of Quaternary sediments and has been largely mapped using shallow seismic data. Shallow seismic profiles and borehole evidence suggest that this clay sequence rests unconformably on Kimmeridgian strata (Figure 7) and is itself unconformably overlain by Upper Cretaceous Chalk strata (Enclosure 1). This latter unconformity, from the limited evidence available, lies close to the base of the Albian, red chalk horizon. Many of the commercial wells in the sheet area were drilled near to the axes of the major salt pillows and have proved only a very thin Lower Cretaceous

BOREHOLE 81/43

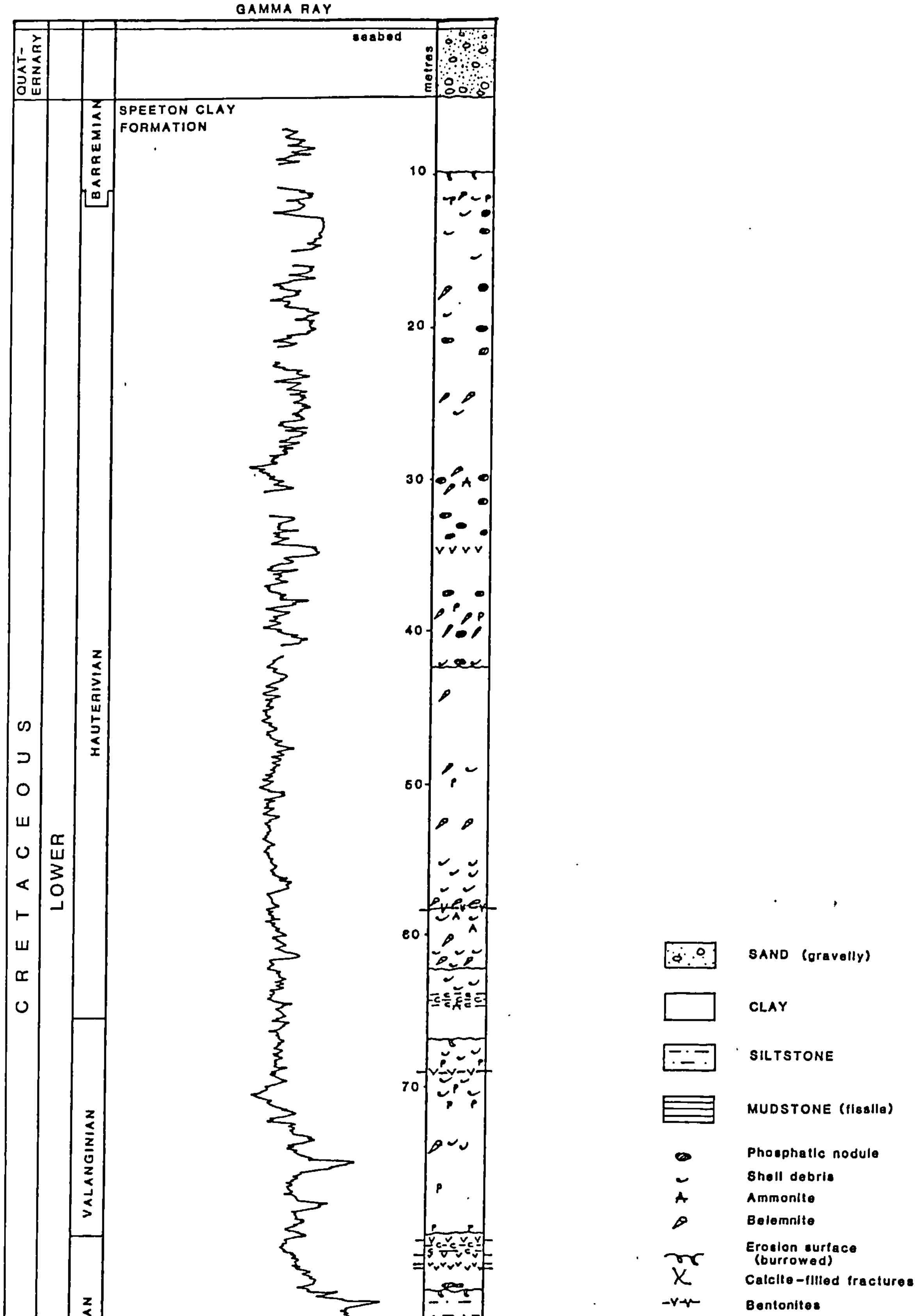


Figure 9. 8 Summary log of borehole 81/43.

succession. Company composite logs often suggest that the oldest sediments in the sequence are of Barremian age, however, it has recently been shown in the Northern North Sea that many of the thin Lower Cretaceous sequences preserved over structural highs are highly condensed and may comprise representatives of many or all of the Lower Cretaceous stages, rather than represent a single isochronous event within the basin (Rawson and Riley 1982).

9.9.2 Upper Cretaceous (Cenomanian to Early Maastrichtian, Chalk Group)

A thick Upper Cretaceous sequence covers much of the sheet area. Reactivation of the salt pillows probably occurred during the Upper Cretaceous as the thickest chalk sequences occur (1000m+) in the rim synclinal structures in the south-west of the sheet area. The Chalk succession preserved in the northern part of the sheet area (c.600m) lies on the western margin of the new Late Cretaceous depocentre centred further to the east along the present axis of the North Sea. The base Chalk seismic reflector is probably the most easily mapped seismic marker in the North Sea Basin, on both shallow and deep seismic profiles (Figure 10) and can also be readily picked on the downhole log responses in commercial wells from the area. The Chalk Group comprises a monotonous sequence of white chalk sediments which become increasingly argillaceous towards the base of the sequence. The sequence may be divided into a number of lithostratigraphic units on the basis of marked changes in downhole geophysical log responses. The most prominent geophysical log marker within the chalk equates with the **Black Band or Plenus Marl.** This thin carbonaceous clay seam is known from biostratigraphic data to mark the Cenomanian / Turonian boundary in the North Sea Basin (Hart and Bigg 1981). The Black Band has been cored in two BGS boreholes (81/40 see Chapter 8, 82/20 , Figure 9.11) and comprises a unit of dark grey to black, shaly,

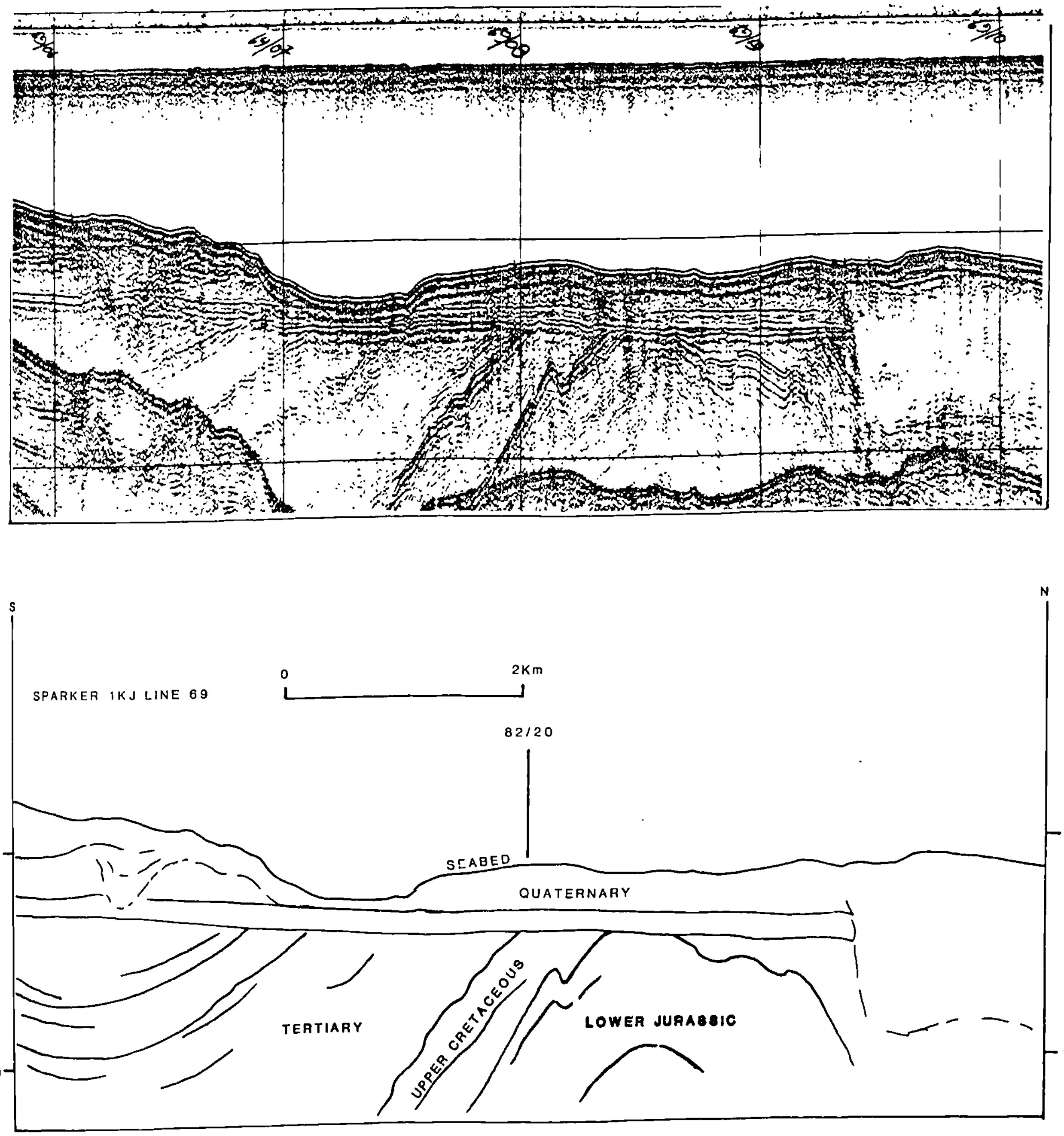


Figure 9.9 Sparker profile showing the base Upper Cretaceous (Chalk Group) reflector.

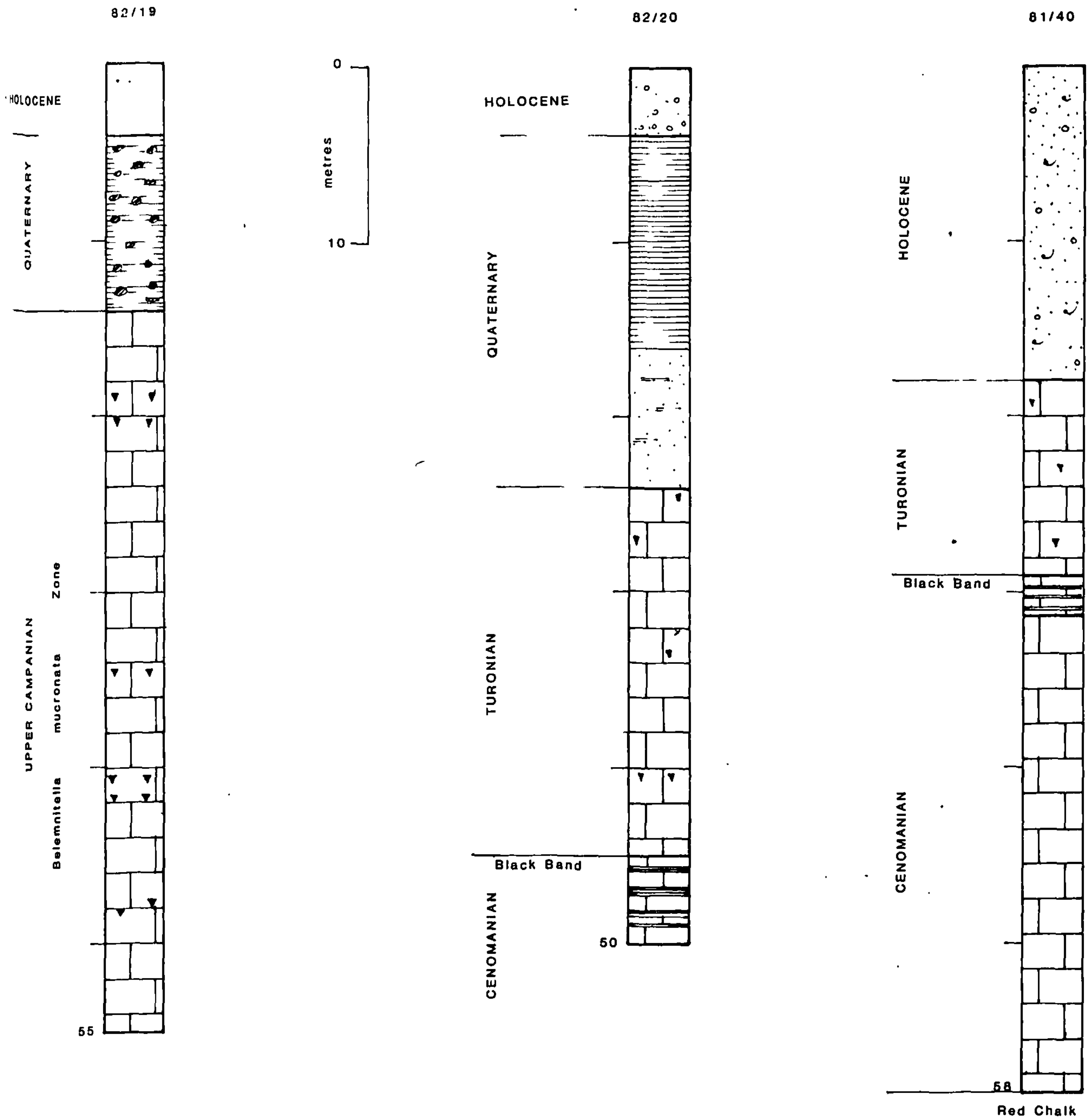


Figure 9.10 Summary logs of BGS Chalk boreholes
81/40, 82/19 and 82/20,

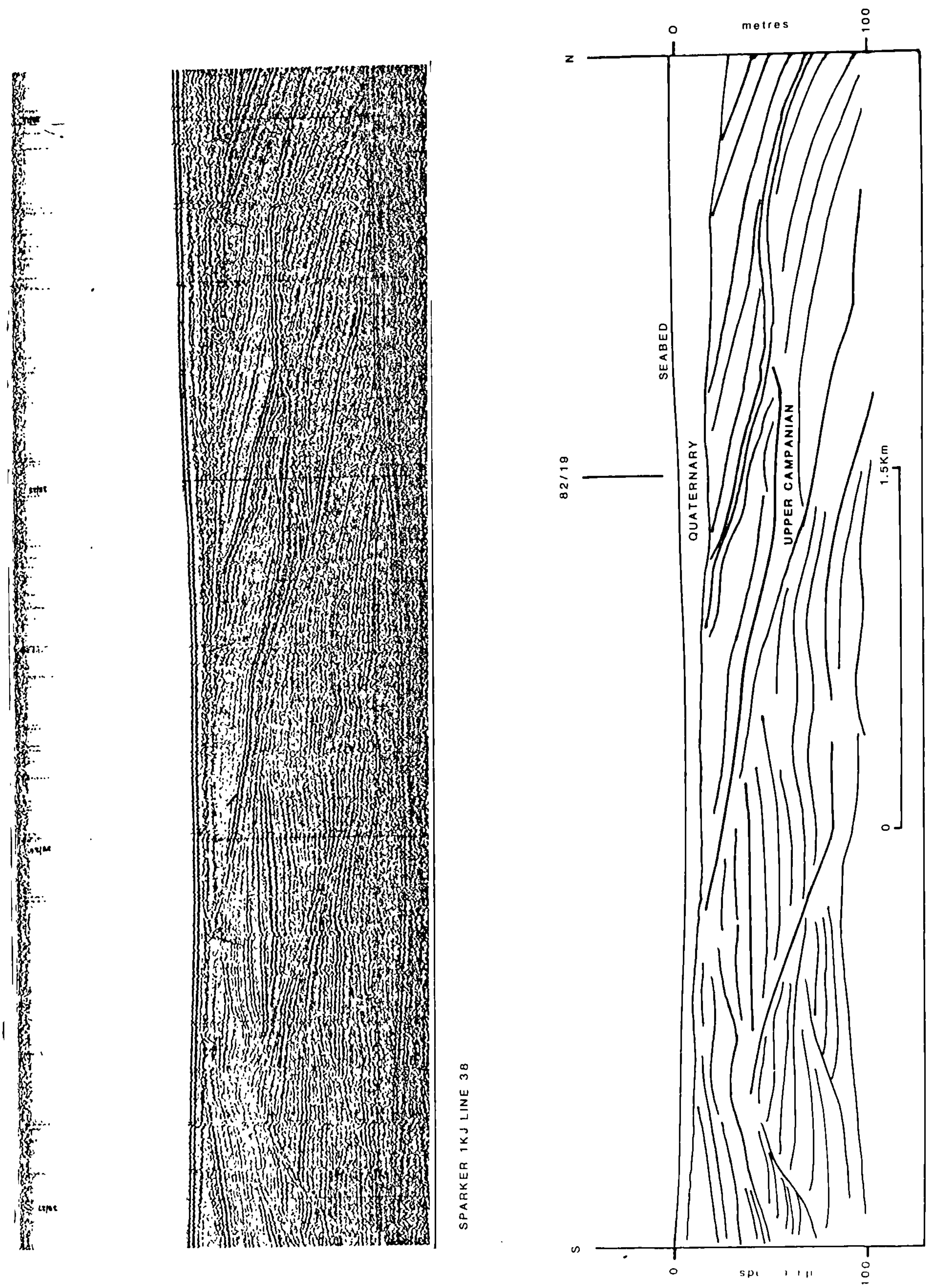


Figure 9.11 Sparker profile illustrating the undulating reflectors of the carbonate shoals and channels of the Upper Campanian sequence in quadrant 43.

organic-rich, non-calcareous clay. The Black Band overlies off-white and greenish-grey, flintless, argillaceous chalks of Cenomanian age. The flinty chalk sequence overlying the Black Band, in the sheet area, ranges from Turonian to Early Maastrichtian in age. Short cores have been drilled in this sequence and the stratigraphy of these cores is summarised in Figure 9.10. The Chalk sequence on the shallow seismic profiles predominantly shows a well-bedded seismic character. However, in some profiles the seismic reflectors show the development of broad shoals and banks within the sequence (Figure 9.11). Borehole 82/19 cored a chalk sequence within these undulating seismic reflectors and the abundant foraminiferal assemblages proved the sequence to be of Upper Campanian age (K. Ball pers comm. 1982).

9.10. Tertiary

Tertiary sediments rest with marked unconformity on Upper Cretaceous chalk strata. Sample evidence suggests that much of the Maastrichtian chalk succession is absent across the sheet area having either not been deposited or having been removed during an Early Palaeocene tectonic phase of uplift. Deposition only recommenced in the Late Palaeocene in the area (Lott et al 1983). The Tertiary sequence reaches a maximum thickness of about 500m thick in the sheet area and continues to thicken eastwards. Three cored boreholes drilled by the BGS (81/45,81/46A and 82/21) cored strata ranging over the Late Palaeocene to Late Eocene microfaunal zones SB2 to NSB6b of King (1983). The succession cored in the boreholes comprised a monotonous sequence of clays, but is notable for the occurrence, in the Late Palaeocene - Early Eocene part of the sequence, of a series of 74 thin bentonite horizons. This Late Palaeocene - Early Eocene volcanic episode is widely documented throughout the North Sea Basin and is known as the Ash - Marker (Figure 9.12; Lott et al 1983).

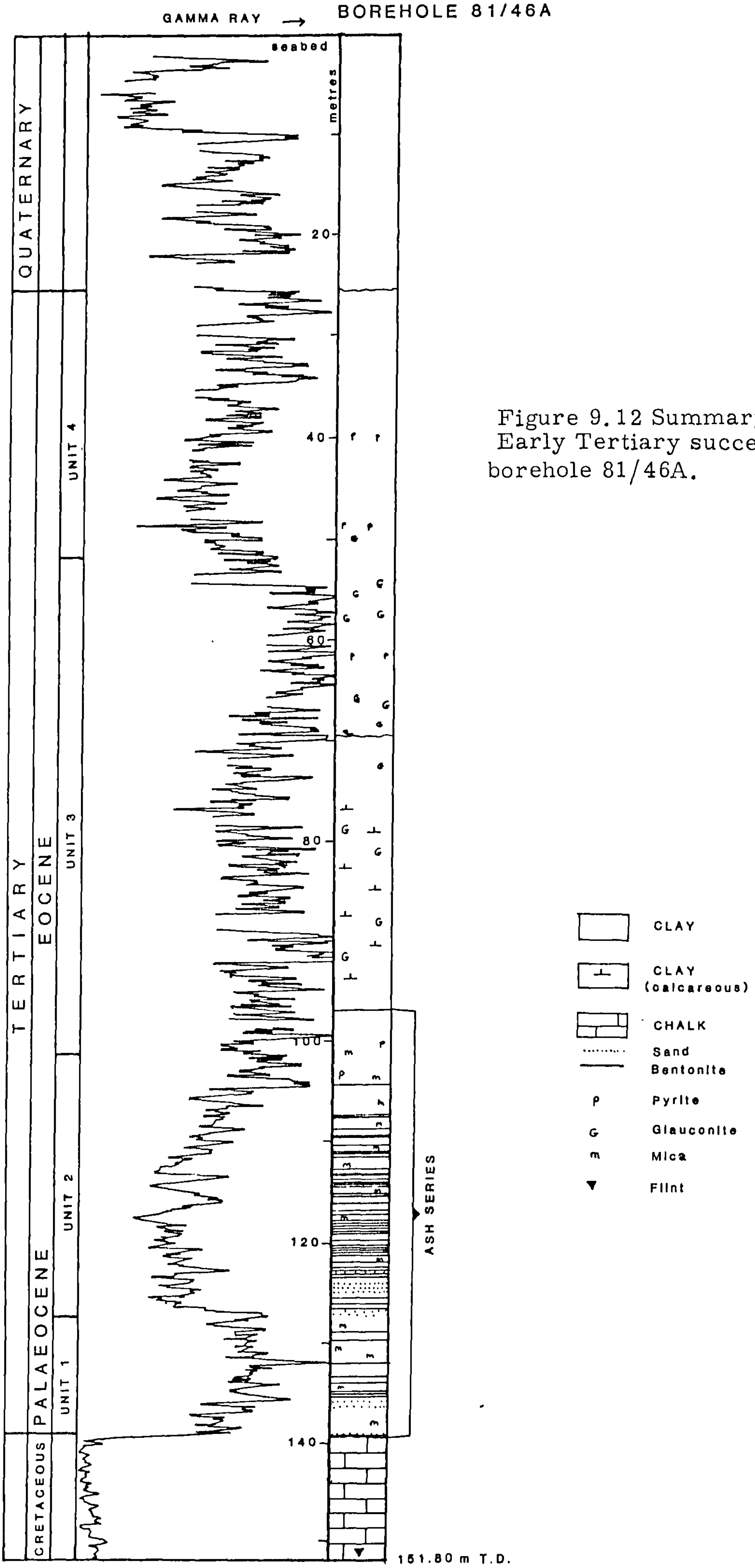


Figure 9.12 Summary log of the Early Tertiary succession of BGS borehole 81/46A.

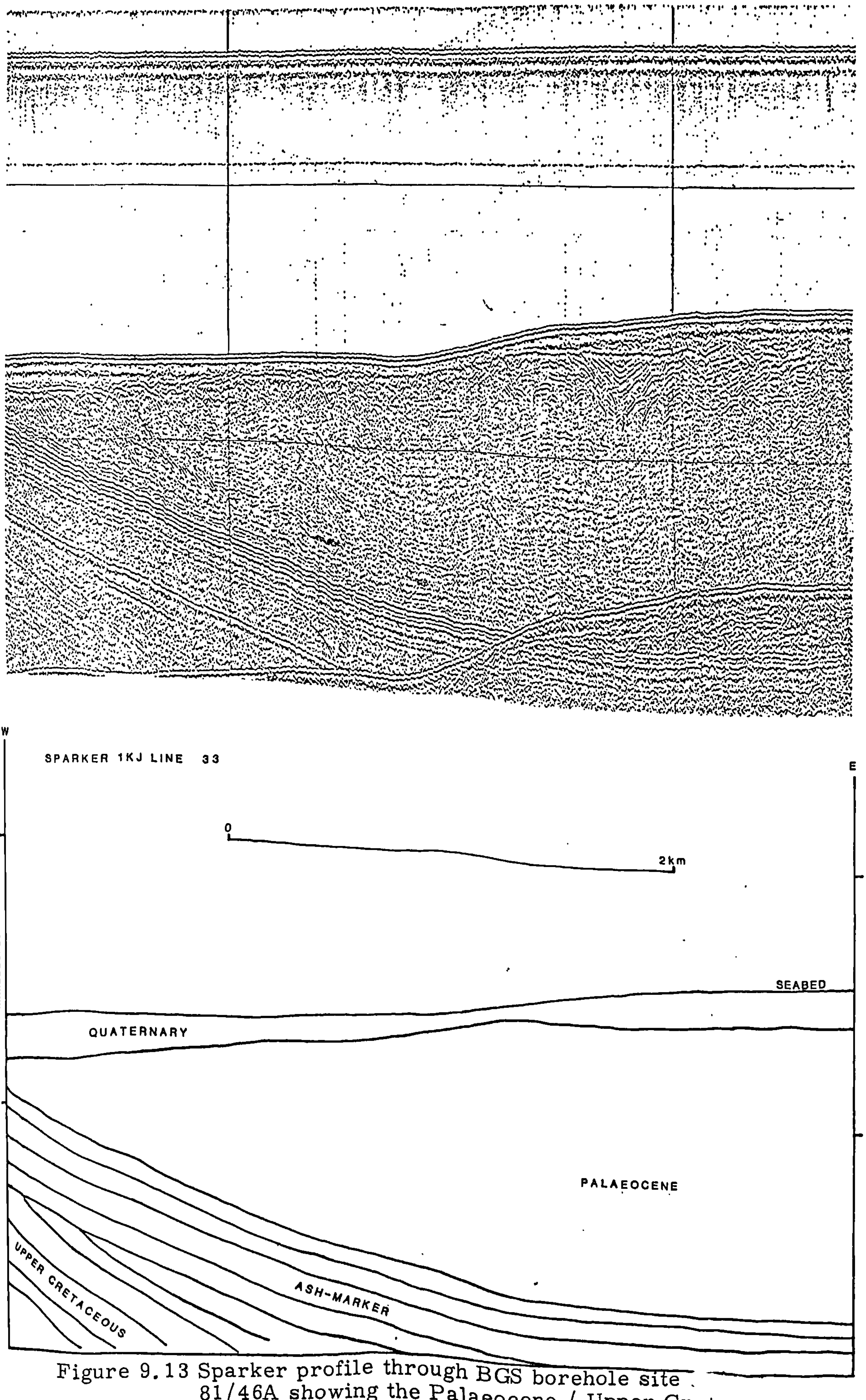


Figure 9.13 Sparker profile through BGS borehole site 81/46A showing the Palaeocene / Upper Cretaceous boundary and the Ash-Marker.

Seismic sections through the Tertiary sequence show a comparatively well- bedded sequence of strata with a number of prominent seismic reflectors . The Ash Marker itself shows up as a particularly prominent series of reflectors at the base of the sequence (Figure 9.13). The sequence was folded into a series of north-east trending anticlines and synclines probably during the Late Tertiary and it would seem likely that further movement of the Zechstein salt pillows occurred at this time to enhance the development of these structures.

9.11. Quaternary

Pleistocene sediments in the sheet area reach up to 500m in thickness (Enclosure 2) and continue to thicken eastwards towards the axis of the main depocentre. These sediments, based on rather limited biostratigraphical control, range from Early Pleistocene to Holocene in age and rest with marked unconformity on folded Eocene or older strata within the sheet area. Borehole and sample evidence shows that the sequence comprises a thick lower, pre- glacial interval of fluvial and marine interbedded clays and sands of Early to Middle Pleistocene age, and a thinner upper interval of Late Pleistocene age, characterised by glacially derived tills and clays. The sequence can be divided seismically into a number of units each with a distinct seismic character (Enclosure 2). The lowermost seismic unit is particularly interesting because of the development, within the interval, of a series of north westward prograding sandy beds. This sequence is much more fully developed further south and represents the northward encroachment into the North Sea Basin of the Early Pleistocene deltas of the North West German river systems.

The Pleistocene sequences of the sheet area are largely covered by a sequence of post-Flandrian marine sands which ranges in from a thin veneer to c.25m in thickness. Muddy sediments are only found in the deeper water area (>80 metres water depth) of the Outer Silver Pit in the south-east corner of the sheet.

10. Summary

10. Summary

1. The lithostratigraphy, thickness and distribution of the Late Triassic (Rhaetian) strata of the Winterton Formation within the U.K. sector of the Southern North Sea Basin is described and illustrated using downhole geophysical well log correlations. The Winterton Formation is shown to extend eastwards beneath the Jurassic sequence throughout the Basin. Core material from an offshore borehole drilled through the Winterton Formation is correlated in detail with its onshore equivalent, the Penarth Group. The Winterton Formation reaches a maximum thickness of c.75m in the offshore area and is divided into two primary lithostratigraphic units which can be traced throughout the basin. The upper unit, which has a maximum development of c.30m in thickness, comprises grey-brown mudstones which are probable correlatives of the Lilstock Formation of the Penarth Group. The lower unit, which has a maximum thickness of c.44m, is more variable in lithology and comprises shaly, dark grey to black, fossiliferous mudstones interbedded with fine grained sandstones, of probable fluvio-deltaic origin. This unit is shown to correlate with beds of the Westbury Formation of the Penarth Group. The Late Triassic succession of the Southern North Sea Basin is closely similar in lithology to the sequences known from parts of the Norwegian-Danish Basin.

2. The Jurassic succession of the U.K. sector Southern North Sea Basin is a remnant of a much more extensive basin of deposition isolated by extensive uplift and erosion during the Late Jurassic and Early Cretaceous. A suite of maps showing the present day thickness and

distribution of Lower, Middle and Upper Jurassic strata within the U.K. sector of the North Sea Basin is presented.

The Jurassic succession of the offshore area is divided into a number of lithostratigraphic units, on the basis of their downhole log respnses, which are correlated in detail with the onshore sequences of Eastern England. The most complete Jurassic sequences are preserved and concealed beneath the thick Cretaceous succession of the East Midlands Shelf. This Shelf area was particularly stable throughout the Jurassic and many of the lithostratigraphic subdivisions of the onshore sequence are shown to extend into the offshore area with little change in thickness or facies. The marine oolitic limestones of the Lincolnshire Limestone Formation, for example, extend eastwards across almost the whole of this Shelf area before passing laterally into the paralic, clastic sequences of the more rapidly subsiding Sole Pit Trough.

The Jurassic succession thickens dramatically into the Sole Pit Trough (c.950m preserved) and also in locallised syndepositional, rim-syncinal troughs marginal to the main Zechstein salt diapirs. These sequences are, however, incompletely preserved primarily due to the subsequent inversion and erosion of the Sole Pit structure during the Late Jurassic—Early Cretaceous. During the Middle and Upper Jurassic the Sole Pit Trough occupied a structural setting similar to that of the Cleveland Basin of North Yorkshire. The sediments within this Trough therefore show greater lithological affinities, particularly in the Upper Jurassic, with the successions of the Cleveland Basin rather than with those of the East Midlands Shelf. The Corallian oolitic limestone facies, for example, is shown to occupy an arcuate outcrop extending from the Cleveland Basin into the Sole Pit

Trough but passes westwards into a siltstone and mudstone dominated successsion over the East Midlands Shelf.

At present the Sole Pit area forms a complex north-west trending broad anticlinal arch with Triassic and Jurassic sediments cropping out along its length at or near seabed. The structure is pierced by a number of major salt diapirs.

3. Sandstones occur throughout the Middle Jurassic successions of Eastern England. A lithostratigraphic subdivision of these sandstones has been made utilising changes in their heavy mineral assemblages. The presence or absence of Apatite, which is related to changes in acidity in the original depositional environment, for example, enables marine and non-marine sandstone units respectively to be distinguished. The assemblages are also distinctive enough to permit correlation between individual boreholes and with the limited material available from the Middle Jurassic successions of the offshore area.

The sandstones of the Middle Jurassic are shown to have a predominantly local provenance from the Pennine - Mid-North Sea Highs, however, a small but important exotic component (kyanite, staurolite and chloritoid) is present, derived from the regionally metamorphosed terrains of the Scottish Massif.

The occurrence of severely etched kyanite and staurolite grains in sandstones from these East Midlands sequences is surprising given the structural stability of the area, but may be explained by the flushing of the sediment pile by corrosive fluids expelled from sediments deeper in the basin, perhaps during inversion of the Sole Pit Trough.

In the heavy mineral assemblages recovered from the sandstones of the Kellaways Rock and Sand (Callovian), euhedral Apatite grains were noted which , it is suggested, may be indicators of a volcanic component to the assemblages.

4. Upper Jurassic mudstone sequences of Kimmeridgian age (baylei to hudlestoni zones) are described and the lithological similarity of the sequences to the type Kimmeridge Clay of the onshore area, illustrated by the presence throughout of small scale rhythmic cycles of sedimentation including thin oil-shale horizons, is noted. The Kimmeridge Clay rests on thinly developed Ampthill Clay before passing down into thin sandstones and oolitic limestones of the Upper Calcareous Grit and Coralline Oolite Formations respectively. The Kimmeridgian / Ryazanian unconformity shows a change from typical Kimmeridge Clay lithologies through a transitional interval of organic-rich, non- calcareous siltstones and mudstones of Ryazanian age, only thinly represented at Speeton, into calcareous mudstones of more typical Speeton Clay facies.

5. The Early Cretaceous Speeton Clay Formation is locally well developed in the northern part of the Southern North Sea Basin. The Speeton Clay sequence cored in the offshore area ranges from Ryazanian to Albian in age and is correlated in detail with the type succession at Speeton. Seven thin bentonite horizons are identified in the Ryazanian to Hauterivian sequence (E to Lower B Beds) and can be correlated with bentonites known at Speeton. A second group of nine bentonite horizons in the Late Aptian to Early Albian interval are also identified. This latter suite of bentonites has probable correlatives in the Lower Cretaceous Fullers Earths of Southern England and also with bentonites recorded in the Aptian / Albian succession of North West Germany. The upper boundary between the Speeton Clay Formation and Upper Cretaceous white chalk shows a

complex transitional sequence of red mudstones, brown-grey mudstones, variegated siltstones and red chalk. An unconformity is present separating the Late Aptian and Early Albian sequences.

6. Detailed mapping of the sub-Pleistocene geology of the California sheet has enabled the stratigraphy and structural development of the area, in relation to the Southern North Sea Basin as a whole, to be documented. Within the sheet area representatives of all the post-Permian successions are present at outcrop and are mapped using shallow seismic profiles. The stratigraphy and lithologies of these sequences are described from cored borehole data.

The present complex, sinuous outcrop patterns within the sheet are a consequence of the erosion of the many salt induced anticlinal structures present in the area. These anticlines were formed by extensive movement of the thick Zechstein salt sequences which underlie most of the area. These salt sequences are shown to have moved spasmodically since the Middle Triassic and have exerted considerable syndepositional control on sedimentation patterns particularly during the Jurassic and Early Cretaceous.

Two phases of volcanic activity in the North Sea area are documented from the strata cored in the sheet area. The first in the Lower Cretaceous reflecting a volcanic source, possibly within the basin and the second, represented by 74 thin tuff bands in the Palaeocene mu dstones, reflecting volcanicity occurring at the rifted Greenland / North European plate boundary.

11. References

11. References

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APPENDIX 1

Thickness of Jurassic and Rhaetian sediments in released commercial wells from the U.K. sector of the Southern North Sea Basin. (Depths in metres below Kelly Bushing, thicknesses in metres).

WELL NO.	BC	BUJ	TUJ	BMJ	TMJ	BLJ	TLJ	TJ	RH	*
36/13-1	959					?1030	44	44		
36/15-1	1324					?1367	43	43		
37/10-1	1675					?1733	59	59		
38/1-1	1756					?1831	75	75		
41/18-1						184	184	184	12.5	
41/20-2	thin Rhaetic at outcrop									
41/24A-1						221	221	221	18.6	
41/25-1						203	203	203	?	
42/13-1	1021					?1068	47	47		
42/23-1	A	262	262	318	56	664	346	574	23	
42/28-1	518	834	316	976	142	1260	284	742	20	
42/28-2	945	1272	324	1296	23	1495	200	547	21	
42/29-1	613	769	156	919	749	1267	348	654	27.4	
42/30-1		?153	153	515	362	1073	558		P	
43/11-1	392					?495	103	103	22.9	
43/15-1	785					973	189	189	20.1	

43/17-1	base Quaternary			123		177	54	54	P
43/20-1	647					924	277	277	P
43/21-1						504	414	414	22.3
44/11-1	1082					?1233	151	151	P
47/3-1	823	945	122	1048	103	1419	371	596	21
47/3-2	694	829	135	952	122	1335	383	641	18.9
47/4-1x	535	716	181	774	58	?1268	494	735	26
47/8-1	628	779	151	812	33	1063	251	435	21
47/8-2	617	835	218	876	40	1117	260	600	24.7
47/9-1	494	661	167	899	238	1264	365	770	18.6
47/9-2	758	982	224	1042	60	1322	280	564	24.1
47/9-3		1031		1224	193	1875	651		21.9
47/13-1	806	963	158	1042	79	1239	197	433	20.1
47/13-2	869	997	174	1080	82	1267	187	398	20.4
47/14-1	869	1002	133	1081	78	1261	179	393	19.8
47/14-2	873	1006	133	1084	78	1266	182	393	21.6
47/14-3	874	998	124	1075	77				20.7
47/14-4	875	1006	131	1084	78	1269	185	394	21
47/15-1	884	1043	159	1194	151	1503	309	619	27.4
47/15-2	1073	1193	156	1268	75	1422	153	385	?
47/18-1	545	857	312	936	79	1192	256	647	17.1
47/20-1	861	1039	178	1113	74	1309	195	444	18.3
47/25-1	679			967		1213	247	534	P
47/25-2	543	750	207	780	30	1024	235	481	P
47/29-1	300	530	230	558	28	767	209	467	24
48/6-2	Base Quaternary			72		565	493	493	P
48/6-3			"	75		660	585	585	P
48/6-4			"	72		563	491	491	P

48/6-5		140	73	331	191	1043	709	976	P
48/6-6	Base Quaternary			72		564	492	492	P
48/6-7			"	90		565	475	475	P
48/6-10				315		1039	724	953	P
48/6-16	Base Quaternary			85		641	556	556	P
48/7-1			"	84		378	294	294	
48/7-2			"	86		256	170	170	
48/7-3			"	150		768	618	618	
48/7-4	150	440	290	787	347	1537	750	1387	
48/11-1	984	1102	118	1265	163	1652	337	668	18
48/11-2	806	964	158	1064	100	1328	264	522	10
48/11-3	947			1170		1493			9.7
48/12-1	Base Quaternary			161		652	491	491	38
48/12-2		"	v thin	247		853	606		36
48/13-1			"	186		396	210	210	61
48/13-2A			"	97		383	286	286	54
48/17-1	595	735	176	779	42	1015	456	456	
48/18-1				723		1261	538		53.9
48/18-2	444D			756		1164	408	720	50
48/19-1	330			100		399	299	399	69
48/20-1	Base Quaternary			128		605	477	477	
48/21-2	645	878	233	937	74	1154	217	509	
48/22-1	415	606	191	637	31	919	282	504	
48/22-2	435			665		942	278	507	
48/22-3	572	762	190	819	56	1059	239	488	
48/23-1	906	1121	215	1177	56	1309	133	403	
48/25-1	Base Quaternary			137		189	52	52	
48/28-1		?315		356	41	614	258	285	P

48/29-1	?176	235	495	260	319	P
48/29-2	?189	213	497	284	308	P
48/29-3	?309	335	592	257	283	P
48/29-4	?173	248	563	315	390	P
48/29-6	?173		575	402	402	P
48/30-1x	703		?742	39	39	
48/30-2	114		?310	196	196	
48/30-3	130		?311	181	181	
48/30-7	318		452	134	134	
49/6-2			850	131	131	
49/6-3	1668		2160	492	492	
49/11-1			976	311	311	26
49/12-3	539		855	316	316	63
49/12-5			701	128	128	52
49/12-6			1807	217	217	
49/16-1	516		719	203	203	P
49/16-2	456		592	136	136	46
49/16-3	183		913	730	730	66
49/16-4	647		707	71	71	55
49/16-5	744		1291	744	744	57
49/16-6	201		734	533	533	73
49/17-5	957		1096	139	139	41
49/17-6	510		656	146	146	39
49/17-9			889	490	490	40.5
49/21-2			592	278	278	68.6
49/21-3			573	109	109	
49/21-4			620	251	251	55.8
49/22-1			896	192	192	18

49/22-2		871	260	260	50
49/22-3		805	234	234	51
49/28-3	Lower Jurassic thin				60
49/28-4	"				54
49/28-5	"				77.7
49/28-6		632	218	218	78
52/5-11	Lower Jurassic thin				34
53/1-1		319	144	144	38.7
53/1-2	Lower Jurassic thin				28.6
53/1-4		394	171	171	
53/2-2	Lower Jurassic thin				48.8
53/2-3	"				43.9

* BC Base Cretaceous

BUJ Base Upper Jurassic

TUJ Thickness " "

BMJ Base Middle Jurassic

TMJ Thickness " "

BLJ Base Lower Jurassic

TLJ Thickness " "

TJ Total Thickness of Jurassic

RH Thickness Rhaetian

APPENDIX 2

Heavy Mineral analysis

Sample preparation

1) approximately 30gm. of sample was disaggregated by gentle percussive crushing action (using a morter and pestle) to avoid damaging the grains.

2) The crushed sample is placed in a bowl and a small quantity of water added. Further disaggregation is then carried out using an ultra-sonic probe.

3) The disaggregated sample is then wet-sieved through a 31 micron (5 Phi) sieve to collect all grains of coarse silt size or larger.

4) Dry sample in oven.

5) The sample is now dry sieved to collect the 63-125 micron fraction (3-4 Phi).

6) Separations are made at a consistent grain size

i. to minimise hydraulic effects on the assemblages.

ii. 63-125 microns approximates most nearly to the thickness of a polished thin section, so that the optical properties and therefore identification of the non-opaque grains is facilitated by comparison with standard optical tables.

iii. the sandstones examined in the boreholes predominently lie within the grain size limits 3-4 Phi.

7) Separation of the light and heavy mineral grains from the 63-125 micron fraction was made using the apparatus and techniques described by Carver (1971) and is summarised briefly as follows:-

The principle involved in the separation of heavy minerals relies on the variation in specific gravity of different minerals, with the separation being effected by using organic liquids of known specific gravity and floating off the 'light' fraction.

Heavy minerals are defined in this study as those grains with a specific gravity greater than 2.9. Such separations commonly include both opaque and non-opaque grains. In this study the non-opaque grains were of particular interest though variations in the opaque minerals, which largely include siderite and pyrite, were also noted.

Apparatus

The apparatus used consists of a small filter funnel, to which is attached a short length of transparent flexible tubing. The tubing is closed using a screwclamp fixed about 30mm below the neck of the funnel. The funnel and attachments is suspended from a retort stand at a height convenient for the insertion and collection of the organic liquids and their mineral residues in a flask placed beneath the tubing. Four such pices of apparatus were used.

Method

1) The apparatus is placed in a fume cupboard and the flexible tubing is closed using the screwclamp.

2) Bromoform of specific gravity 2.9 is poured carefully into the filter funnel so as to achieve a level approximately 20mm below the funnel rim, thus creating a column of liquid through which the mineral grains fall during the separation.

3) The disaggregated sieved sample is poured into the bromoform, care being

taken that the sample is not allowed to collect on the walls of the filter funnel above the level of the liquid.

4) The bromoform and sample is stirred gently with a glass rod, again avoiding splashing of the sample onto the funnel walls, to prevent choking at the throat of the funnel.

5) Separation by settling is allowed to take place over a period of 24hrs or longer - bearing in mind that longr periods allow some loss by evaporation of the bromoform. During this period gentle squeezing of the flexible tubing just above the clamp will ensure heavy mineral grains do not become lodged on the walls of the funnel.

6) When satisfied that an adequate heavy fraction is trapped above the clamp at the base of the tubing, the fraction is removed as follows.

7) A second filter funnel with filter paper is placed in a suitable container beneath the suspended funnel. The screwclamp is opened carefully and the bromoform and heavy mineral fraction is allowed to flow onto the filter paper beneath. The clamp is closed and the heavy fraction and container removed. A third funnel and clean filter paper are then substituted to recover the remaining light mineral fraction and bromoform from the separating funnel.

8) The heavy and light fractions are then washed into a second container using methylated spirits and allowed to dry. Any bromoform and methylated spirit from such washings may be recovered later.

Grain mounting of the heavy mineral fraction

In order to undertake identification of the heavy mineral grains separated by the above method the grains are mounted on a glass slide, for examination beneath a petrological microscope.

1) A glass slide is heated gently on a hot plate.

2) Canada Balsam (or an equivalent fixative) is smeared over a smll area of

the slide and allowed to heat gently.

3) The separated heavy mineral grains are then sprinkled from the filter paper evenly over the smeared portion of the slide so as not to allow an excessive build up of grains at any particular point.

4) A glass cover slip is then carefully placed over the mineral grains and fixative and firmly but gently pressed down to exclude air bubbles.

5) The slide mount is then allowed t 'cook' gently on the hot plate for 20-30 minutes.

6) The edges of the glass slide coverslips are subsequently sealed by running a heated blade around the margins of the coverslip.

7) Finally excess Canada Balsam is removed by immersing the slide in methylated spirit and gently scrubbing with a stiff brush. The slide is then washed in clean, warm, soapy water.

Grain Counts

The heavy mineral grains were counted using ribbon traverses across the slide. 200 grains were counted on each slide and the slides were then scanned for any rare or unusual grains. The grain counts were recalculated to 100%.

Description of the heavy mineral grains

Nettleton Bottom borehole

Apatite

Apatite occurs in almost all the residues examined and is particularly common in the Lincolnshire Limestone Formation. The grains are usually well-rounded, sometimes showing ragged edges. In the basal Kellaways Sand residues a number of fresh euhedral apatite grains were observed, a possible indication of reworking of volcanic detritus.

Chloritoid

Chloritoid occurs sparsely in all the main lithostratigraphic units of the sequence, but proved most abundant in the Thorncroft Sand (Upper Estuarine Series). The grains are usually small irregularly shaped, platy flakes which are pale blue in colour.

Garnet

Garnet is common throughout the sequence, but is particularly abundant in residues from the sands beneath the Thorncroft Sands (Upper Estuarine Series). The grains are generally colorless to pale reddish-brown, angular with some etch pits or more rarely may be severely etched. Inclusions are common in some grains. Preferential etching of the inclusions produces a 'swiss-cheese' - like appearance of pits and holes in some of the grains. Mammillated surfaces are commonly seen on some grains.

Kyanite

Kyanite occurs rarely in the residues. When present the grains are slightly ragged tabular shapes.

Rutile is the third most abundant mineral in the residues, it occurs in a wide variety of colours ranging from yellow to deep red-brown. Prismatic and needle-shaped grains are common, with rare geniculate twins occuring.

Staurolite

Staurolite occurs in most of the residues and is particularly abundant in the sandy interval of the Blisworth Clay. The grains are a distinctive straw - yellow colour, with severely etched saw-toothed grains particularly common.

Tourmaline

Tourmaline occurs commonly in many of the residues as prismatic and tabular grains. Colours range from pale green to yellow-brown.

Zircon

Zircon is common in all the residues, but is particularly abundant in the sands above and including the Thorncroft Sands (Upper Estuarine Series). The grains show a wide variety of shapes including small, euhedral grains, well-rounded grains and bullet or bead-shaped types.

Brown Moor borehole

Apatite

Apatite grains are particularly abundant in the Cloughton Formation. The grains are commonly egg-shaped, often with extremely ragged edges. Euhedral grains were noted in the Kellaways Rock and Sand, again possibly suggestive of volcanic activity in adjacent area at this time i.e. early Callovian.

Chloritoid

Chloritoid occurs sporadically throughout the sequence usually as platy grains or flakes.

Garnet

Garnet is common throughout the sequence, but is particularly abundant in the Scalby Formation and underlying sand units. Grains vary widely from fresh, angular forms to mammillated and more rarely, severly etched types. 'Swiss-cheese' type, etched grains are also prominent.

Kyanite

Kyanite is common in many of the residues. Grains may be long prismatic shapes or stumpy forms. Both forms show jagged terminations to the grains. Some grains show an undulose extinction pattern.

Rutile

Rutile is common in all the residues. Grains are usually prismatic or acicular forms and range from amber to dark reddish-brown in colour. Geniculate twins are occasionally seen.

Staurolite

Staurolite occurs frequently in the residues as straw yellow, saw-toothed grains. Grains may be long prismatic forms or short stumpy types. 'Concertina'-like heavily etched forms commonly occur.

Tourmaline

Tourmaline is abundant in most of the residues. Grains are generally prismatic forms with rounded terminations. A wide range of colours from brown to pale green occur.

Zircon

Zircon is common in all the residues but is most abundant in the Kellaways Rock and Sand at the expense of garnet. Grains may vary from small rounded bead-like shapes to more euhedral forms. Occasional zoned zircons were noted.

South Cave borehole

Apatite

Apatite grains were rare in the residues. The grains that occur are egg-shaped forms. Within the Kellaways Rock and Sand sequences some euhedral stumpy prisms were noted. The occurrence of such euhedral apatite grains has been noted in both the Brown Moor and Nettleton Bottom boreholes, and a possible volcanic origin has been suggested.

Chloritoid

Chloritoid flakes were only rarely seen in the residues.

Garnet

Garnet forms, with zircon and rutile, one of the three most abundant minerals in the non-opaque residues. Grains occur in a variety of forms varying from fresh, angular shapes to mammillated, moderately etched types. The grains are generally colourless to very pale reddish-brown, occasionally with many inclusions.

Kyanite

Kyanite is quite common in the Kellaways Sand and Rock and is less common in the underlying units. Grains occur as large prismatic forms with jagged terminations.

Rutile

Rutile is very abundant in the Upper Estuarine Series and Lincolnshire Limestone Formation, but less common in the overlying units. Grains vary from long tabular types, broken prismatic forms to geniculate twins. Colours range from amber to deep reddish-brown.

Staurolite

Staurolite occurs in all the residues usually as stumpy straw yellow prisms. Saw-toothed forms occur only rarely.

Tourmaline

Tourmaline occurs abundantly in many of the residues. Grains are generally tabular-euhedral forms with a wide range of colours from pale yellow-brown to rarer reddish-brown forms. Grains showing overgrowths were occasionally noted.

Zircon

Zircon is particularly abundant in the Kellaways Rock and Sand residues. Grains vary from small, well rounded forms to euhedral types. Occasional zoned grains were noted and rare purple zircons are present.

Alandale borehole

Apatite

Apatite was not recorded in any of the residues.

Chloritoid

Chloritoid flakes were extremely rare in the residues.

Garnet

Garnet grains are abundant in the Kellaways Rock and Sand residues and less common in the underlying sands. Grains vary from fresh, angular forms through mammillated types to occasional more severly etched grains.

Kyanite

Kyanite commonly occyrs throughout the sequence but is particularly abundant in the residues from the Upper Estuarine Series. Stumpy and prismatic grains are common, usually with fine saw-tooth terminations.

Rutile

Rutile grains are common in all the residues. Grains are prismatic or acicular types varying from yellow to red-brown in colour.

Staurolite

Staurolite commonly occurs in all the residues. The grains are deep yellow, prismatic or stumpy forms with poorly developed saw-toothed terminations.

Tourmaline

Tourmaline is abundant in many of the residues. Grains are generally euhedral, tabular forms with rounded terminations. The grains show a wide range of colours.

Zircon

Zircon is the most abundant mineral in all the residues. It occurs both as well rounded and euhedral forms. Purple zircons were occasionally noted.

APPENDIX 3

Bedrock samples collected over the California Sheet

All samples were submitted for micropalaeontological work and details of the results are kept in the unit files of the Marine Geological Research Group, BGS, Keyworth, Nottingham.

West 54/00

site number sample description

54/00/136 MUDSTONE, dark grey, calcareous, silty, weathered top.

150 SILTSTONE, dark brownish-grey, pyritic, fissile, very muddy.

179 MUDSTONE, dark grey to black, calcareous, fossiliferous.

180 SANDSTONE, pale grey, friable, fine grained, well sorted.

181 SANDSTONE, pale greenish-grey, fine-grained, muddy, micaceous, laminated. on SILTSTONE, grey, muddy, laminated, micaceous, with paler grey fine sand pockets.

183 SILTSTONE, grey, laminated, muddy with pale grey fine sandy pockets.

187 MUDSTONE, dark grey to black, calcareous, fossiliferous, poorly fisile to blocky.

192 LIMESTONE, white to iron stained creamy-brown, fossiliferous, coarse-ribbed bivalve, sandy.

193 MUDSTONE, dark grey, poorly calcareous, very silty, micaceous.

195 MUDSTONE, dark grey, calcareous, fossiliferous, (ammonite debris), fissile.

196 MUDSTONE, grey, calcareous.

198 LIMESTONE, white to off-white, oolitic, weathered. ?CORALLIAN.

200 LIMESTONE, white to cream, oolitic, sandy, weathered. ? CORALLIAN.

212 CHALK.LATE CAMPANIAN.

215 CLAY

216 CLAY,

213 CLAYSTONE, olive-grey, non-calcareous. EARLY EOCENE, YPRESIAN

261 CHALK, EARLY CENOMANIAN.

262 CHALK.

263 CHALK, EARLY TURONIAN.

264 CHALK, SANTONIAN.

265 CHALK, CONIACIAN TO SANTONIAN.

277 CHALK, MIDDLE CAMPANIAN.

278 CHALK, LATE CAMPANIAN.

279 CHALK, LATE CAMPANIAN.

280 CHALK.

285 CHALK, LATE CAMPANIAN.

288 SANDSTONE, pale brown-grey, friable, calcareous.

293 MUDSTONE, dark brownish-grey, very silty, fissile, paper shale.

295 SANDSTONE, pale grey, calcareous, cemented, very fine grained.

296 SILTSTONE, brown-grey, sandy, non-calcareous, very friable.

298 LIMESTONE, white to cream, bioclastic debris, sandy.

299 MUDSTONE, black, fissile, non-calcareous.

301 MUDSTONE, medium grey, moderately calcareous, fissile.

302 MUDSTONE, medium brownish-grey, calcareous, fissile, silty.

303 MUDSTONE, medium brownish grey, calcareous, fossiliferous, silty, fissile.

304 MUDSTONE, medium grey, very silty, micaceous, calcareous, poorly laminated.

305 MUDSTONE, blue-grey, blocky fracture, calcareous.

306 MUDSTONE, grey, poorly calcareous, fissile.

307 MUDSTONE, grey, poorly calcareous, poorly laminated.

308 MUDSTONE, grey, calcareous, blocky, paler silty patches.

309 MUDSTONE, grey, calcareous.

312 MUDSTONE, grey, calcareous.

313 MUDSTONE, black, fissile, very fossiliferous, silty, calcareous.

315 LIMESTONE, oolitic.

316 SANDSTONE, buff, very hard, well cemented, calcareous.

320 MUDSTONE, dark grey, blocky, bituminous, calcareous.

337 CHALK.

338 CHALK.

346 IRONSTONE, dark green, oolitic, dense, friable to hard. ?DOGGER, MIDDLE JURASSIC.

348 SANDSTONE, pale grey to grey brown, friable to hard, calcareous, very fine grained.

351 CHALK.

357 SANDSTONE, pale grey, calcareous, very fine grained, friable.

361 MUDSTONE, grey, calcareous, fissile.

362 MUDSTONE, grey, poorly calcareous, fissile.

363 MUDSTONE, grey, silty, calcareous, fissile.

364 MUDSTONE, dark grey, calcareous, silty, fissile.

365 MUDSTONE, dark grey, poorly calcareous, fissile.

366 MUDSTONE, dark grey, blocky, poorly calcareous.

367 MUDSTONE, dark grey, blocky, poorly calcareous, belemnite fragment.

368 MUDSTONE, grey.

390 SANDSTONE, buff, very fine, non-calcareous.

392 LIMESTONE, brown to buff, oolitic, bioclastic debris, sandy.

394 SILTSTONE, grey, muddy, blocky, calcareous.

395 MUDSTONE, grey, silty.

396 SANDSTONE, grey, carbonaceous, friable, non-calcareous.

397 LIMESTONE, white, sandy.

399 LIMESTONE, white to cream, oolitic, weathered.

400 MUDSTONE, dark grey, non-calcareous, blocky.

401 MUDSTONE, dark grey, poorly calcareous, blocky.

406 MUDSTONE, dark grey, calcareous, blocky.

408 MUDSTONE, pale green-grey, non-calcareous. ?RHAETIAN.

409 MUDSTONE, green-grey, non-calcareous.

410 MUDSTONE, dark grey, silty, non-calcareous.

416 MUDSTONE, dark grey, blocky, calcareous, silty.

417 MUDSTONE, dark grey, silty, bioturbated, very calcareous, blocky.

418 LIMESTONE, white to cream, oolitic, friable. CORALLIAN.

419 LIMESTONE, cream, oolitic, bioclastic, hard.

420 LIMESTONE, white, oolitic, friable, weathered.

423 LIMESTONE, white to grey, oolitic, bioclastic, hard.

425 SANDSTONE, buff, very fine grained, carbonaceous, friable.

426 SANDSTONE, white, friable, finely interlaminated with carbonaceous (black and brown lignite) plant debris, fragment of lustrous light 'cannel' coal.

427 SANDSTONE, buff to pale brown, hard to friable, non-calcareous, very fine grained.

429 IRONSTONE, green, sandy, very calcareous. ? DOGGER, MIDDLE JURASSIC.

434 MUDSTONE/SILTSTONE, dark to pale grey, non-calcareous.

439 MUDSTONE, grey, very silty, non-calcareous, blocky fracture.

440 SILTSTONE, dark grey, very muddy, non-calcareous.

442 MUDSTONE, dark grey, calcareous, silty.

443 MUDSTONE, dark grey, blocky, soft, moderately calcareous.

449 MUDSTONE, brown-grey to grey, non-calcareous, laminated.

451 MUDSTONE, dark grey, non-calcareous, blocky fracture.

452 MUDSTONE, grey, non-calcareous, silty pockets, micaceous.

453 SANDSTONE/SILTSTONE, brown-grey, very calcareous, sub-fissile.

454 LIMESTONE, orange-brown to yellow, friable, sandy-weathered top. When fresh -LIMESTONE, pale grey, glauconitic, sandy,

460 MUDSTONE, dark grey, calcareous, fissile.

471 SANDSTONE, pale grey, calcareous, fine-medium grained, bioclastic debris.

472 MUDSTONE, dark grey, pyritic, patches, non-calcareous, belemnite fragment.

477 CHALK, EARLY MAASTRICHTIAN.

488 LIMESTONE, dark greenish-grey, oolitic.

489 LIMESTONE, creamy-white, oolitic, bioclastic.CORALLIAN.

499 SILTSTONE, pale grey to white, non-calcareous, clean, quartzose.

507 CHALK, EARLY MAASTRICTIAN.

509 CHALK, CONIACIAN - CAMPANIAN.

510 CHALK, EARLY TO MID-CAMPANIAN.

512 CHALK

514 CLAY, dark grey, calcareous, carbonaceous, micaceous.

516 SANDSTONE, grey, calcareous, very fine grained, glauconitic.

549 CLAY, brown, non-calcareous.

552 CHALK, EARLY MAASTRICHTIAN.

558 CHALK, LATE CAMPANIAN - EARLY MAASTRICHTIAN.

560 CHALK, CAMPANIAN.

562 CHALK.

567 MUDSTONE, dark grey, non-calcareous.

571 SANDSTONE, pale grey, muddy, non-calcareous, very fine grained, friable.

572 SANDSTONE, pale grey, calcareous, hard, sparsely oolitic, glauconitic.

602 SILTSTONE, pale grey, micaceous, dark organic rich laminae, non-calcareous, sliightly muddy.

604 SILTSTONE, grey, fossiliferous, calcareous.

605 SILTSTONE, medium grey, sandy, fossiliferous.

606 MUDSTONE, black, fissile, fossiliferous, ammonites common. KIMMERIDGIAN (Aulocostephanus mutabilis Zone - DR.B.M.COX pers comm.).

607 SILTSTONE/SANDSTONE, pale grey to black, muddy, finely laminated organic rich laminae, slightly fissile.

609 MUDSTONE, brown-black, blocky fracture, fossiliferous.

610 SANDSTONE, pale grey, muddy, very fine grained, micaceous, non-calcareous.

611 SANDSTONE, pale grey, muddy, very fine grained, micaceous, non-calcareous.

612 SANDSTONE, pale grey, clean, friable, very fine grained, slightly carbonaceous on MUDSTONE, dark green, oolitic, fossiliferous. ? HACKNESS ROCK.

614 SANDSTONE, dark grey, very fine grained, friable, very muddy.

616 SANDSTONE, buff to white, loose to friable, foraminifera present, coal fragments.

Bedrock samples California Sheet

East 54/+01

site number   sample description

54/01/73 MUDSTONE, red, silty, grey green siltstone and very fine grained sandstone band. ? TRIASSIC.

ENCLOSURES 3, 4 & 5

PROCEEDINGS OF THE YORKSHIRE GEOLOGICAL SOCIETY, VOL. 45, PART 4, PP. 235-248, 1985

Mid-Cretaceous stratigraphy of a cored borehole in the western part of the Central North Sea Basin

G. K. Lott, K. C. Ball and I. P. Wilkinson

SUMMARY: A borehole (81/40) drilled in the western part of the Central North Sea Basin cored a sequence of Cretaceous strata ranging from Barremian to Turonian in age. This succession of calcareous mudstones and chalks has been divided into six lithostratigraphical units, two of which include a number of thin volcanic tuff bands (bentonites) of Late Aptian to Early Albian age. The lithologies of each of these units are described, together with a preliminary biostratigraphy for the sequence based upon their diverse foraminiferal and ostracod assemblages. Range charts for the foraminifera and ostracods are presented and the regional significance of the sequence is discussed.

Borehole 81/40, drilled by the Marine Geology Research Group of the British Geological Survey (BGS) in the Central North Sea (56°08.03′N 0°43.60′W), cored a 94 m sequence of Cretaceous strata ranging in age from latest Barremian to Turonian. Drilling and coring terminated at a depth of 112.6 m. At this site, shallow seismic profiles indicate that there are a further 100 m of Lower Cretaceous strata unconformably overlying Triassic sediments. Six lithostratigraphical units were recognised within the cored Cretaceous succession of the borehole:

1. A lowermost unit of calcareous greenish grey, in places brown, mudstones, with paler, hard, limy bands (Barremian – Middle Aptian).
2. Calcareous red mudstones (Middle – Late Aptian).
3. Grey-brown mudstones with eight thin volcanic tuff bands (Late Aptian – Early Albian).
4. Thin variegated silty mudstone beds (Early Albian) with a single volcanic tuff band.
5. A thin 'red chalk' sequence (Middle Albian – Early Cenomanian).
6. An uppermost unit of white chalk (Cenomanian – Turonian).

The lithology of each of these units is described (GKL) in the following account. The sequence yielded a rich microfauna of foraminifera (KCB) and ostracods (IPW), enabling a preliminary biostratigraphy to be established. The location of the borehole is shown in Figure 1 and a graphic log in Figure 2. Details of micropalaeontology samples are shown in Table 1. The recorded ranges of selected foraminifera are shown in Figure 3, and the ranges of selected ostracods in Figure 4.

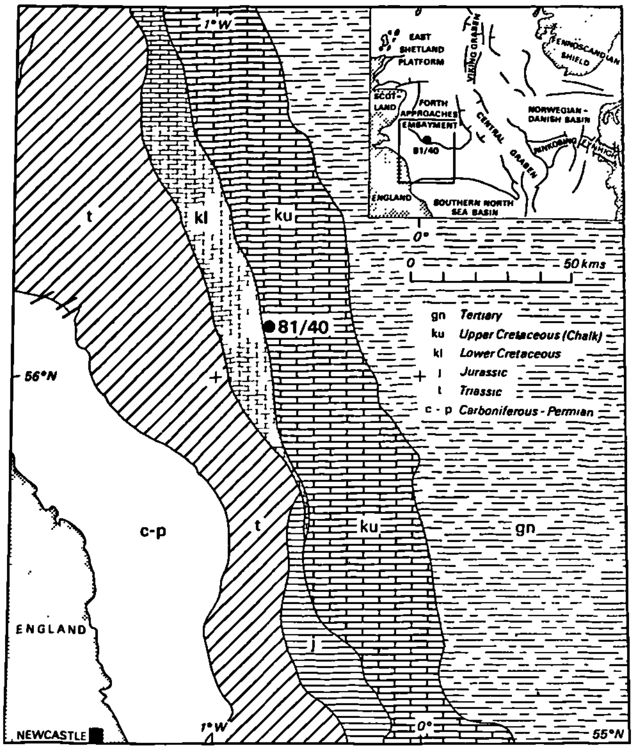


Fig. 1. Location of the borehole.

1. GREENISH GREY MUDSTONES

(82.98-112.6 m TD)

1.1. Lithology

This unit consists predominantly of greenish grey, strongly calcareous, burrow-mottled mudstones. These mudstones are distinguishable from those of the overlying unit only on their colour. Foraminifera-speckling of the core is a common feature and bioclastic debris is abundant. Small (up to 0.04 m across), pale brown-rimmed phosphatic nodules commonly occur. Thin paler, hard, *Chondrites*-mottled marly limestone units are present at 94.22-96.84 m and 98.07-99.94 m, each showing a cyclic change from basal white marly limestones to pale greenish grey marls.

1.2. Foraminifera

The foraminiferal fauna is characterised by a diverse and abundant assemblage of benthonic species including

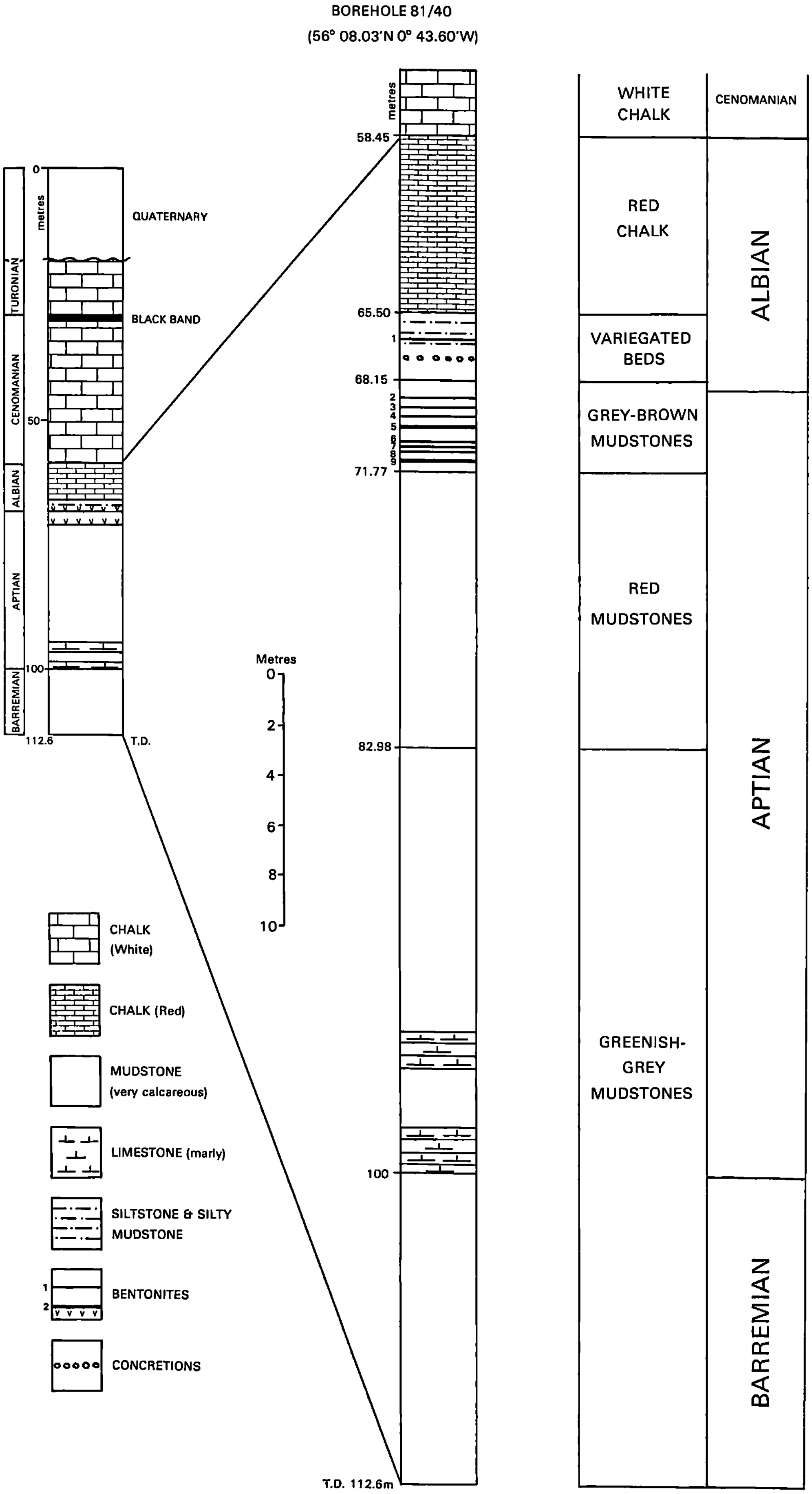


Fig. 2. Summary log of the borehole.

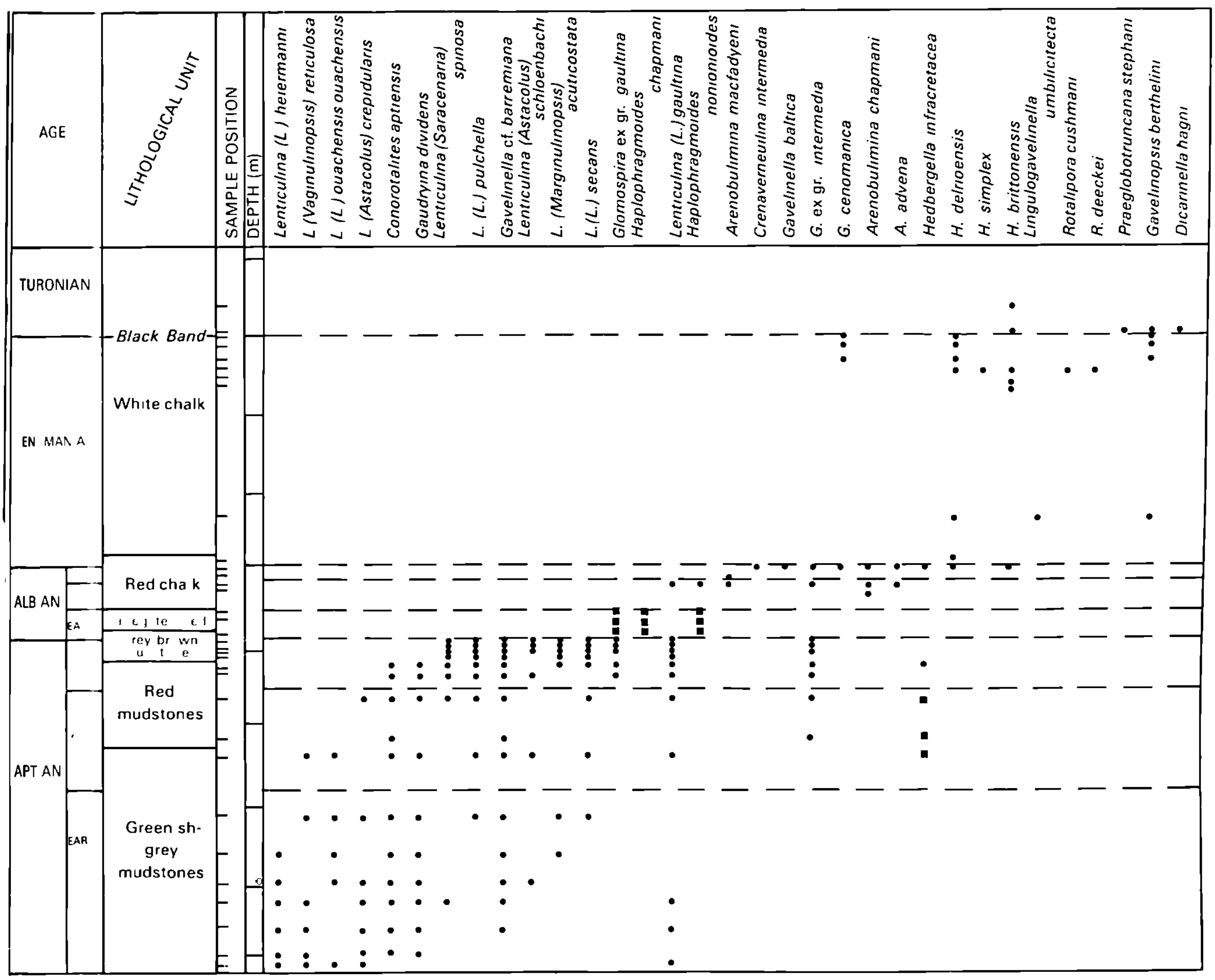


Fig. 3. Range of occurrence of selected foraminifera taxa recorded in Borehole 81/40.
(■ = present in abundance.)

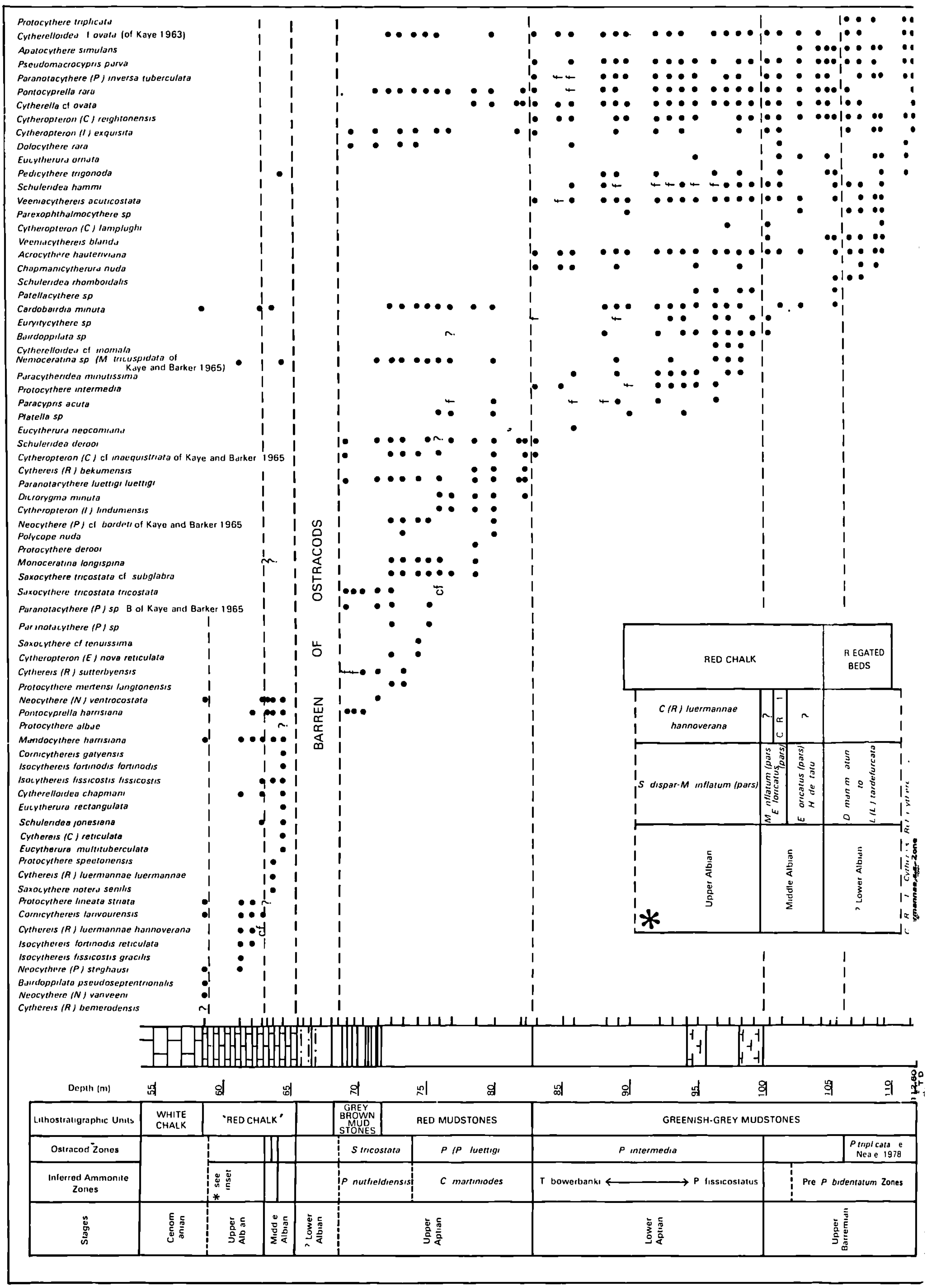


Fig. 4. Range of occurrence of selected ostracod taxa recorded in Borehole 81/40.

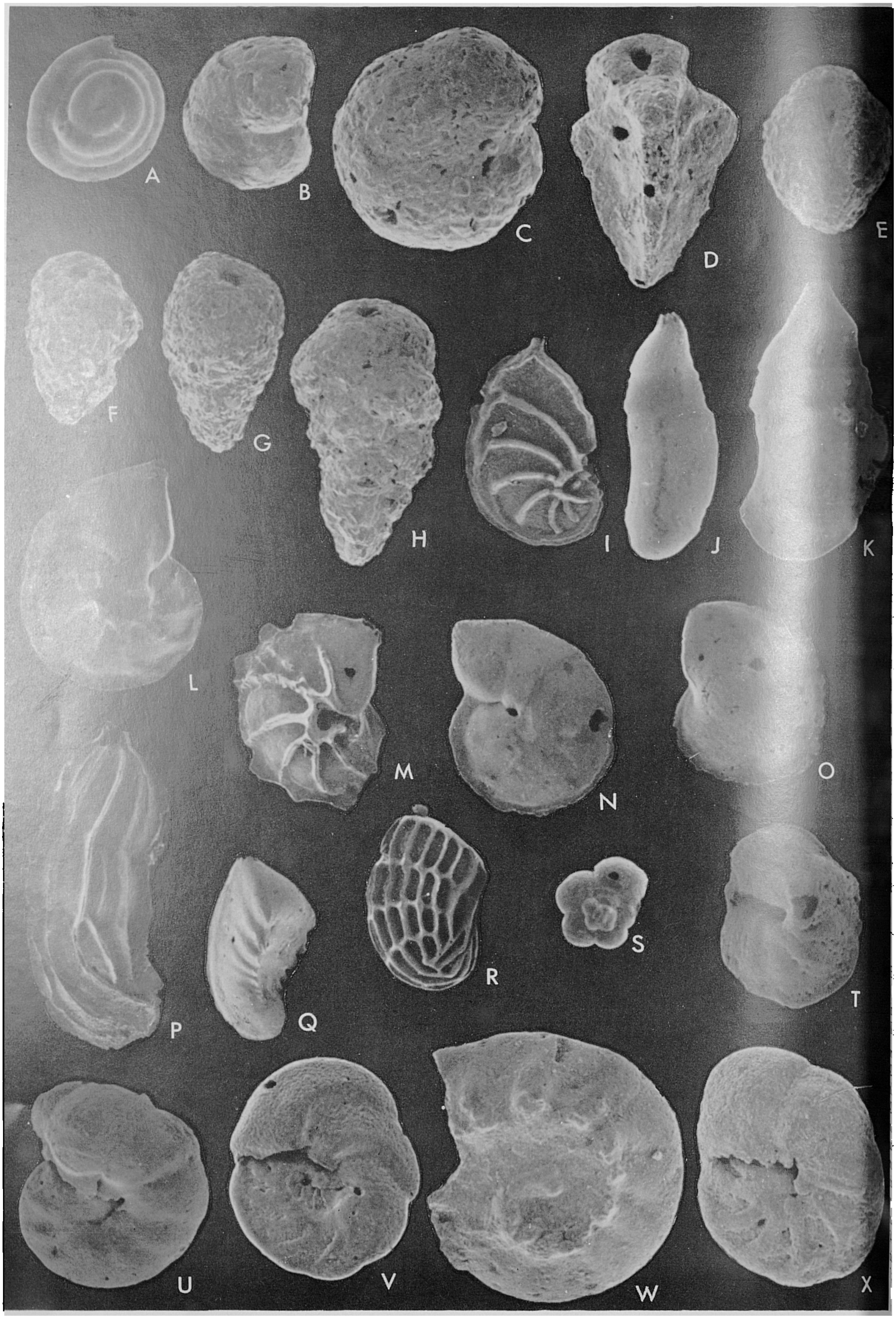
Table 1.
Details of samples examined for foraminifera (f) and ostracods (o).
All samples and slides are housed with the British Geological Survey, Keyworth.

Depth (m)	*Sample No. (CSB)*	*Microfossils*	*Depth (m)*	*Sample No. (CSB)*	*Microfossils*	*Depth (m)*	*Sample No. (CSB)*	*Microfossils*
26.80	4829	f	68.84-68.94	4903	fo	93.20-93.30	4927	o
29.40	4830	f	69.33-69.43	4904	fo	94.10-94.20	4928	o
30.00	4831	f	69.90-70.02	4905	fo	95.05-95.15	4929	o
30.30	4832	f	70.68-70.78	4906	fo	95.96-96.09	4930	f
31.30	4833	f	71.64-71.74	4907	fo	96.60-96.70	4931	o
33.00	4834	f	72.68-72.78	4908	fo	97.44-97.54	4932	o
34.50	4835	f	73.43-73.53	4909	fo	98.20-98.30	4933	o
35.05	4836	f	74.40-74.52	4910	o	99.09-99.19	4934	o
36.50	4837	f	75.34-75.44	4911	o	99.80-99.90	4935	f
52.80	4838	f	76.00-76.10	4912	o	100.62-100.72	4936	o
58.90	4839	fo	76.93-77.03	4913	o	101.22-101.32	4937	o
60.49-60.58	4891	f	77.13-77.23	4914	f	102.15-102.25	4938	f
1.44-61.50	4892	o	78.93-79.03	4915	o	102.90-103.00	4939	o
61.50	4840	f	80.00-80.10	4916	o	104.15-104.25	4940	o
2.42-62.50	4893	fo	82.50	4843	fo	104.77-104.87	4941	o
3.05-63.12	4894	o	82.59-82.69	4917	o	105.44-105.45	4942	o
63.50	4841	f	83.40-83.50	4918	o	106.00-106.10	4943	f
3.55-63.63	4895	o	84.27-84.37	4919	f	106.87-106.97	4944	o
3.94-64.04	4896	o	85.18-85.28	4920	o	107.72-107.82	4945	
64.78-64.88	4897	o	86.08-86.18	4921	o	108.90-109.00	4946	o
5.50-65.60	4898	fo	88.50-88.60	4922	o	109.30-109.40	4947	o
66.39-66.46	4899	fo	89.48-89.58	4923	o	110.65-110.75	4948	f
66.96-67.06	4900	o	90.18-90.28	4924	o	111.61-111.71	4949	o
7.47-67.57	4901	o	91.13-91.23	4925	f	112.05-112.15	4950	f
68.29-68.39	4902	o	92.23-92.30	4926	o	112.60	4828	o

Conorotalites aptiensis (Bettenstaedt) (Fig. 5T), *Gaudryina dividens* Grabert, *G. prædividens* Neagu, *Gavelinella* cf. *barremiana* Bettenstaedt (Fig. 5V) and many species of *Lenticulina* including *L.* (*Astacolus*) *repidularis* (Roemer) (Fig. 5I), *L.* (*Astacolus*) *chloenbachi* (Reuss), *L.*(*L.*) *gaultina* (Berthelin), *L.*(*L.*) *heiermanni* Bettenstaedt (Fig. 5L), *L.*(*L.*) *ouachensis ouachensis* (Sigal) (Fig. 5M), *L.*(*L.*) *pulchella* (Reuss), *L.*(*L.*) *subgaultina* Bartenstein, *L.*(*Vaginulinopsis*) *reticulosa* (ten Dam) (Fig. 5R) and *L.* (*Saracenaria*) *spinosa* (Eichenberg). In north-west Germany and Britain, most of these taxa occur in both the Barremian and the Aptian (Bartenstein 1976a, 1976b, 1978; Bartenstein & Kovatcheva 1982; Crittenden 1982b). However, *L. gaultina* and *L. subgaultina*, which occur in relative abundance at 112.5-112.15 m, have not been reported from strata older than the Early Aptian. Therefore, on evidence of foraminifera alone, the lowest strata in borehole 81/40 are dated as Early Aptian. In contrast, the ostracods (see below) date these strata as Late Barremian. A flood of the small planktonic *Hedbergella infracretacea* (Glaessner) (Fig. 5S) occurs at 84.32 m, indicating the Mid or earliest Late Aptian.

1.3. Ostracoda

The ostracod assemblages from this unit can be broadly divided into two: those from the lower mudstone division which contain Barremian species and those from the limestones and upper mudstone division which lack these forms. The lower mudstone division is characterised by Barremian to Early Aptian species such as *Cytheropteron reightonensis* Kaye, *Veeniacythereis blanda* (Kaye), *Schuleridea hammi* (Triebel) (Fig. 6C) and *Acrocythere hauteriviana* (Bartenstein). Of particular note is the presence of *Protocythere triplicata* (Roemer) in the lowest 6 m of the borehole, for this is the index form of the ostracod zone erected by Christensen (1974), modified by Neale (1978), which extends from the Hauterivian to the middle part of the Barremian. Its upper boundary is ill-defined, though at Speeton it is found in the top part of the Cement Beds, i.e. the Middle B of Kaye (1964). The exact stratigraphical position of this boundary is uncertain,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but it apears to fall within the *O. germanica* (belemnite) Zone which is equivalent to the *A. innexum* to *P.scalare* ammonite zones (Rawson & Mutterlose 1983). Another important ostracod is *Apatocythere (Apatocythere) simulans* Triebel (Fig. 6D), a species that becomes extinct before the *P. bidentatum* (ammonite) Zone of the Late Barremian at Speeton (Neale 1978). In Heligoland, however, it occurs only in the Late Hauterivian and in Germany it extends into the Early Barremian (Bartenstein & Oertli 1975). The present borehole also contains *Schuleridea rhomboidalis* Neale (Fig. 6A) in the lower division and this species has a similar range to *A. simulans* in north-west Europe. Although *A. simulans* and *S. rhomboidalis* do not extend up to the top of the lower mudstone division, the mudstone-limestone contact is here arbitrarily taken to be the Barremian/Aptian boundary but see section 1.2 above.

The limestones and upper greenish grey mudstones contain *Protocythere intermedia* Kaye (Fig. 6J), which was used by Neale (1978) as the zone fossil for the whole of the Early Aptian. This species first appears in the *P. fissicostatus* Zone (?*P. bodei* Subzone) of the Speeton Clay of Yorkshire (Kaye 1962; Neale 1978) and extends up to the *T. bowerbanki* Zone (Neale 1978). *Bairdoppilata* sp (Fig. 6Q) and *Euryitycythere* sp. (Fig. 6S) first appear 0.7 m below the base of the limestone, but a little higher, within the limestone, several other species were recorded for the first time at this horizon, e.g. *Cytherelloidea* sp. (Fig. 6U) (closely related to *C. anomala* Kaye, but with an almost smooth lateral surface), *Nemoceratina* sp. (Fig. 6P) =*Monoceratina tricuspidata* of Kaye & Barker 1965), *Paracytheridea minutissima* (Kaye) (Fig. 6R) and *Paracypris acuta* (Cornuel) (Fig. 6T). A few rare species appear for the first time within the upper greenish grey mudstone, e.g. *Platella* sp. (Fig. 6V), and *Schuleridea hammi* (Triebel) becomes extinct a little below the top (at 86.06 m), but there is no significant difference from the assemblages recovered from the limestones.

2. RED MUDSTONES

(71.77-82.98 m)

2.1. Lithology

The unit consists predominantly of pale to modera reddish brown (10R4/5), strongly calcareous mudstones. The mudstones contain abundant bioclastic debris, including bivalve and belemnite fragments, giving the sediment a gritty texture. Foraminifera speckle the core and glauconite grains are abundant, particularly in association with some large burrow-fill, giving a greenish tinge to the sediment. Pale yellow-brown, calcareous concretions occur at some levels. The base of the unit is marked by an abrupt colour change to pale greenish grey, calcareous mudstones; there is no associated erosion surface or significant lithological change.

2.2. Foraminifera

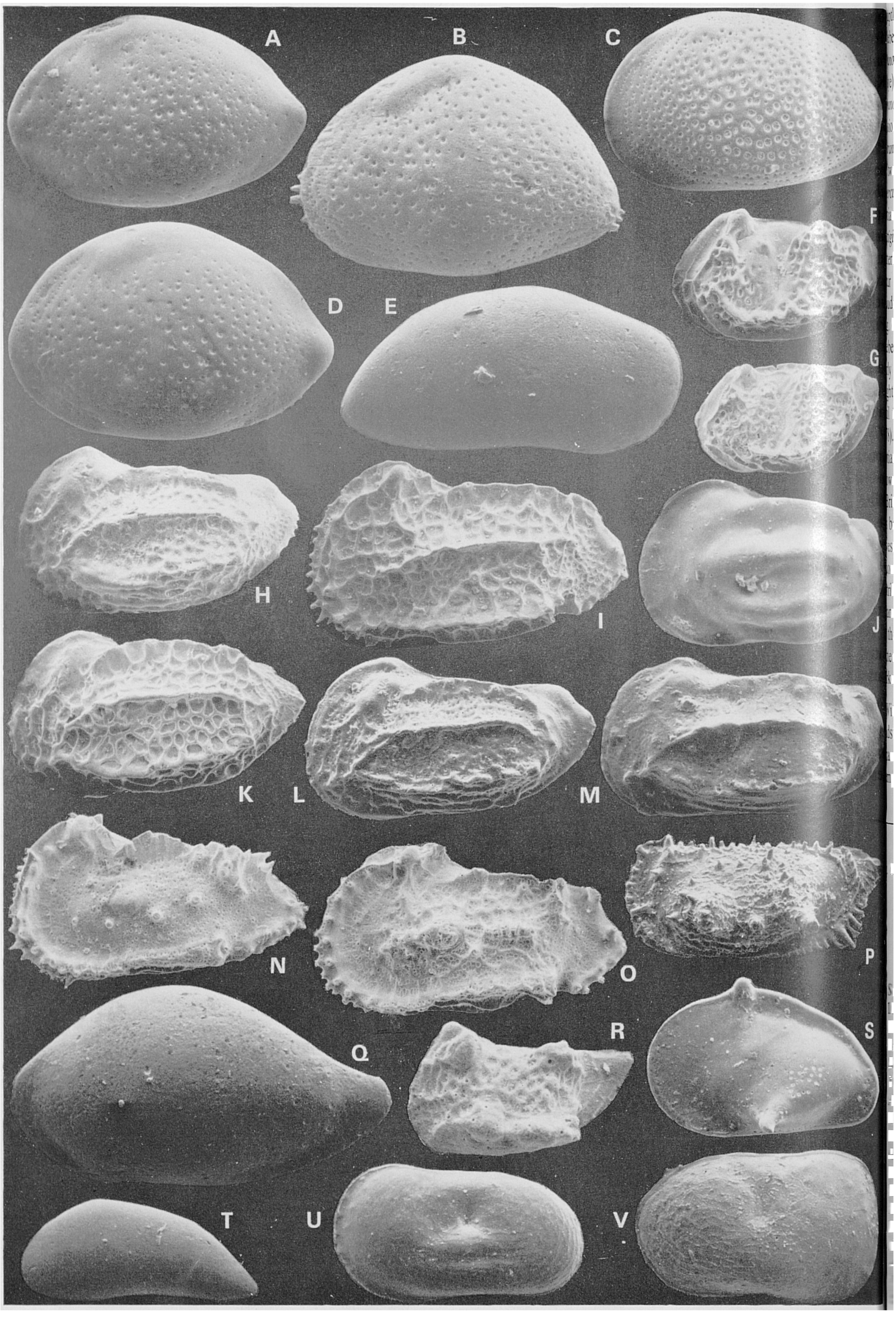
This unit is characterised by a diverse and abundant assemblage of benthonic species including *Conorotalites aptiensis, Gaudryina dividens* (Fig. 5D), *Gavelinella* cf. *barremiana* and *Gavelinella* ex gr. *intermedia* (Berthelin), together with many species of *Lenticulina* including *L. (Astacolus) crepidularis, L.(L). gaultina* (Fig. 5K), *L.(L.) pulchella, L.(L.) secans* (Reuss), *L.(A.) schloenbachi* and *L. (Saracenaria) spinosa* (Fig. 5Q). Comparison with recorded occurrences in north-west Germany suggests a latest Aptian age for this assemblage (Bartenstein 1978; Bartenstein & Kovatcheva 1982). However, the fauna also includes at least two floods of small, red-stained *Hedbergella infracretacea* which are indicative of a Mid or early Late Aptian age (Hecht 1938; Bartenstein & Kaever 1973; Crittenden 1984b).

2.3. Ostracoda

The base of this unit is marked by a sudden change in the fauna. *Acrocythere hauteriviana,* which dominated the faunas of most samples between 109.4 and 83 m,

Fig. 5. Early Cretaceous foraminifera from Borehole 81/40. (All specimens are ×100, except Fig. 5H ×60, and are in the collections of the British Geological Survey, Keyworth.)

A. *Glomospira* ex gr. *gaultina* Berthelin; MPK 4199; 66.42 m.
B. *Haplophragmoides chapmani* Morozova; MPK 4200; 66.42 m.
C. *H. nonionioides* (Reuss); MPK 4201; 66.42 m.
D. *Gaudryina dividens* Grabert; MPK 4202; 72.73 m.
E. *Arenobulimina advena* (Cushman); MPK 4203; 60.54 m.
F. *A. chapmani* Cushman; MPK 4204; 60.54 m.
G. *A. macfadyeni* Cushman; MPK 4205; 62.47 m.
H. *Crenaverneuilina intermedia* (ten Dam); MPK 4206; 60.54 m.
I. *Lenticulina (Astacolus) crepidularis* (Roemer); MPK 4207; 112.10 m.
J. *L. (A.) schloenbachi* (Reuss); MPK 4208; 69.38 m.
K. *L. (L.) gaultina* (Berthelin); MPK 4209; 77.18m.
L. *L. (L.) heiermanni* Bettenstaedt; MPK 4210; 112.10 m.
M. *L. (L.) ouachensis ouachensis* (Sigal); MPK 4211; 84.32 m.
N. *L. (L.) pulchella* (Reuss); MPK 4212; 69.38 m.
O. *L. (L.) secans* (Reuss); MPK 4213; 69.38 m.
P. *L. (Marginulinopsis) acuticostata* (Reuss); MPK 4214; 69.38 m.
Q. *L. (Saracenaria) spinosa* (Eichenberg); MPK 4215; 72.73 m.
R. *L. (Vaginulinopsis) reticulosa* ten Dam; MPK 4216; 112.10 m.
S. *Hedbergella infracretacea* (Glaessner); MPK 4217; 84.32 m.
T. *Conorotalites aptiensis* (Bettenstaedt); MPK 4218; 106.05 m.
U. *Gavelinella baltica* Brotzen; MPK 4219; 60.54 m.
V. *G.* cf. *barremiana* Bettenstaedt; MPK 4220; 106.05 m.
W. *G. cenomanica* (Brotzen); MPK 4221; 60.54 m.
X. *G.* ex gr. *intermedia* (Berthelin); MPK 4222; 60.54 m.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abruptly disappears as do *Veeniacythereis acuticostata* (Triebel) (Fig. 6I), *Protocythere intermedia* (Kaye) and *Paranotacythere* (*Paranotacythere*) *inversa tuberculata* (Kaye) (Fig. 6F). At the base of the red mudstone, *Paranotacythere* (*Paranotacythere*) *luettigi luettigi* Bassiouni (Fig. 6G) evolved from *Paranotacythere* *Paranotacythere*) *inversa tuberculata* by the fusion of the two ventral ribs at their anterior end. *P.*(*P.*) *inversa tuberculata* ranges between the Barremian and Early Aptian throughout north-west Europe, and *P.*(*P.*) *luettigi luettigi* has been recorded from the Upper Aptian Sutterby Marl of Lincolnshire. Other species which occur for the first time in the borehole at this level include *Schuleridea derooi* Damotte & Grosdidier Fig. 6B) and *Cythereis* (*Rehacythereis*) *bekumensis* Triebel (Fig. 6N). The former was recorded from the Early Aptian in France (Damotte 1971) and the Isle of Wight (Kaye 1965), but did not enter the northern area until the Late Aptian (Kaye & Barker, 1965; Neale 1978). The latter has been recorded throughout the Aptian of Germany, but, according to Neale (1978), is known only from the *P. nutfieldiensis* (ammonite) Zone in Britain. Although *Pontocyprella rara* Kaye (Fig. 6E) has been recovered in small numbers throughout the lowest lithological unit of the present borehole, it becomes the dominant form in the red mudstones. This distribution is similar to that onshore, where the species is rare in the *P. fissicostatus* Zone at Speeton, but is one of the most abundant forms in the Upper Aptian Sutterby Marl of Lincolnshire (Kaye 1965; Kaye & Barker 1965).

Within the middle and upper part of the red mudstones, a form of *Saxocythere tricostata* with a pitted ornament, tentatively assigned to *S. tricostata subglabra* Kemper (Fig. 6L), was found. The more usual reticulate ornament characteristic of *S. tricostata tricostata* (Triebel) (Fig. 6K) was consistently seen in the highest part of the red mudstones and throughout the overlying grey-brown mudstones (72.68-69.33 m). In Germany *Saxocythere tricostata subglabra* evolves into *S. tricostata s. s.* near the base of the *P. nutfieldiensis* Zone (Kemper 1971). *Cythereis* (*Rehacythereis*) *sutterbyensis* Kaye & Barker (Fig. 6O) and *Protocythere mertensi langtonensis* Kaye & Barker (Fig. 6H), which both occur for the first time at a depth of 73.43 m, are useful indicators of this same zone in Lincolnshire (Kaye & Barker 1965; Neale 1978).

3. GREY-BROWN MUDSTONES

(68.15-71.77 m)

3.1. Lithology

The dominant lithology of the unit is uniform, grey-brown, calcareous, burrow-mottled mudstones. There are eight thin bentonites which range from pale greyish green to grey waxy clays, commonly with associated vivid green and red streaks and patches. The bentonites generally have sharp boundaries and in some cases a concretionary base. Grading in the bentonites is not apparent. They range from 0.02-0.16 m in thickness and some show traces of bioturbation. The interbedded grey-brown clays are commonly foraminifera-speckled and contain rare shell debris. The base of the unit is marked by an abrupt colour change to the red mudstones of the underlying unit. The top of the unit is a strongly bioturbated erosion surface.

3.2. Foraminifera

The foraminiferal fauna is dominated by calcareous benthonic species, mainly of the genus *Lenticulina*;

Fig. 6. Ostracoda from the Barremian-Aptian (Lower Cretaceous) of Borehole 81/40.

(All figures are lateral views of left valves, magnified ×75, unless otherwise stated. All specimens are in the collections of the British Geological Survey, Keyworth.)

A. *Schuleridea rhomboidalis* Neale; MPK 4223; depth 107.72-107.82 m.
B. *Schuleridea derooi* Damotte & Grosdidier; MPK 4847; depth 80.00-80.10 m.
C. *Schuleridea hammi* (Triebel); MPK 4224; depth 107.72-107.82 m.
D. *Apatocythere* (*Apatocythere*) *simulans* (Triebel); MPK 4225; depth 107.72-107.82 m.
E. *Pontocyprella rara* Kaye; right valve lateral view; MPK 4848; depth 78.93-79.03 m.
F. *Paranotacythere* (*Paranotacythere*) *inversa tuberculata* Kaye; MPK 4226; depth 94.10-94.20 m.
G. *Paranotacythere* (*Paranotacythere*) *luettigi luettigi* Bassiouni; MPK 4227; depth 82.59-82.69 m.
H. *Protocythere mertensi langtonensis* Kaye & Barker; MPK 4229; depth 72.68-72.78 m.
I. *Veeniacythereis acuticosta* (Triebel); MPK 4231; depth 86.08-86.18 m.
J. *Protocythere intermedia* Kaye; MPK 4230; depth 83.40-83.50 m.
K. *Saxocythere tricostata tricostata* (Triebel); MPK 4228; depth 71.64-71.74 m.
L. *Saxocythere tricostata subglabra* Kemper; MPK 4849; depth 73.43-73.53 m.
M. *Saxocythere* cf *tenuissima* Kemper; MPK 4850; depth 74.40-74.52 m.
N. *Cythereis* (*Rehacythereis*) *bekumensis* Triebel; MPK 4232; depth 82.59-82.69 m.
O. *Cythereis* (*Rehacythereis*) *sutterbyensis* Kaye & Barker; MPK 4233; depth 71.64-71.74 m.
P. *Nemoceratina* sp.; MPK 4851; depth 76.00-76.10 m.
Q. *Bairdoppilata* sp.; MPK 4852; depth 99.09-99.19 m.
R. *Paracytheridea minutissima* (Kaye); MPK 4853; depth 95.05-95.15 m ×125.
S. *Euryitycythere* sp.; MPK 4854; depth 94.10-94.20 m.
T. *Paracypris acuta* (Cornuel); MPK 4855; depth 80.00-80.10 m.
U. *Cytherelloidea* cf *anomala* Kaye; MPK 4856; depth 98.20-98.30 m.
V. *Platella* sp.; right valve lateral view; MPK 4857; depth 76.93-77.03 m.

these include *L.* (*Marginulinopsis*) *acuticostata* (Reuss) (Fig. 5P), *L.*(*L.*) *gaultina*, *L.* (*Astacolus*) *planiuscula* (Reuss), *L.*(*L.*) *pulchella* (Fig. 5N), *L.*(*A.*) *schloenbachi* (Fig. 5J), *L.*(*L.*) *secans* (Fig. 5O) and *L.*(*L.*) *rotulata* (Lamarck). Comparison with recorded occurrences in north-west Germany indicates that this diverse assemblage is of Late Aptian or Early Albian age (Bartenstein 1978; Bartenstein & Kovatcheva 1982). The presence of *L.* (*Saracenaria*) *spinosa*, together with *Gaudryina dividens*, in the lower part of the unit suggests a Late Aptian age (Hecht 1938; Bartenstein & Bettenstaedt 1962).

3.3. Ostracoda

The topmost metre of this unit proved to be barren of ostracods, but the remainder yielded a sparse and poorly preserved fauna of low diversity. A late Aptian age (*P. nutfieldiensis* Zone) is indicated by the presence of *Neocythere* (*Neocythere*) *ventrocostata* Gründel at a depth of 71.64 m and the continued occurrence of *Saxocythere tricostata tricostata* and *Cythereis sutterbyensis* from the unit below. No species characteristic of the highest part of the Aptian and the Early Albian (*H. jacobi* to *D. mammillatum* ammonite zones) was recovered and it is possible that the Aptian/Albian boundary falls in the upper part of this unit.

4. VARIEGATED BEDS

(65.50-68.15 m)

4.1. Lithology

The sediments of this unit show considerable variations both in colour and lithology but are largely non-calcareous. The upper part of the sequence, 65.5-67.04 m, consists of pale reddish-brown (10R4/5.3), non-calcareous siltstones, with waxy mudstone laminae and patches. Bioturbation commonly occurs, often in discrete bands. Colour variations range from yellow-brown to deep red, and there is interbanding of mudstones, siltstones and more rarely, fine sandstone. A single thin purple-red bentonite horizon is developed at 66.60 to 66.61 m within this interbedded sequence. The interval from 67.04 to 67.54 m shows a particularly distinctive development of variegated concretions, set in a muddy matrix, which pass up into finely colour-banded (yellow to dark red) silty clays. Beneath this concretionary layer softer, greenish grey, silty, micaceous clays are developed. The base of the unit is marked by an abrupt change to more uniform burrow-mottled clays.

4.2. Foraminifera

The foraminifera of this unit are dominated by agglutinated benthonic species including *Haplophragmoides nonionioides* (Reuss) (Fig. 5C), *H. chapmani* Morozova (Fig. 5B) and *Glomospira* ex gr. *gaultina* (Berthelin) (Fig. 5A). It has been suggested that the flood occurrences of these agglutinated benthonics are an expression of transgressive phases during the Early-Middle Albian in north-west Europe (e.g. Crittenden 1984a; Price 1977b; Rawson & Riley 1982).

4.3. Ostracoda

This unit was barren of Ostracoda.

5. RED CHALK

(58.45-65.50 m)

5.1. Lithology

The base of the unit is taken at a marked change from siltstones to red-brown chalk, and the top at a comparatively abrupt colour change to off-white chalks of the overlying unit. Bioclastic debris, including bivalve and belemnite fragments, is abundant, giving the sediments a gritty texture. Burrow-mottling commonly occurs throughout the sequence, varying from large sub-vertical and horizontal burrows to a *Chondrites* type. Pale pink patches and off-white haloes are often associated with some of the large burrows and an irregular banding of strongly and weakly bioturbated horizons may be developed. Thin bands of pale brown chalk nodules in a darker muddy matrix occur sporadically, together with subvertical mud-filled fractures and thin dusky-red mudstone bands. Glauconite and pyrite speckling is particularly prominent at some levels.

5.2. Foraminifera

The benthonic foraminiferal fauna is abundant and diverse and includes the agglutinated forms *Arenobulimina advena* (Cushman) (Fig. 5E), *A. chapmani* Cushman (Fig. 5F), *A. sabulosa* (Chapman) and *Crenaverneuilina intermedia* (ten Dam) (Fig. 5H), together with the calcareous forms *Gavelinella baltica* Brotzen (Fig. 5U), *G. cenomanica* (Brotzen) (Fig. 5W) and *G.* ex gr. *intermedia* (Fig. 5X). These are all important members of the known Late Albian-Early Cenomanian fauna in north-west Europe (Barnard & Banner 1980; Carter & Hart 1977; Hart *et al.* 1981; Price 1977b). A Mid-Albian age is indicated for the lower part of the unit by the presence of *A. macfadyeni* Cushman (Fig. 5G) and the associated absence of *G. baltica* and *G. cenomanica*. Dr P. J. Bigg (personal communication 1983) dated the uppermost part of the unit (58.45-58.9 m) as Early Cenomanian based on the occurrence of *Lingulogavelinella jarzevae* (Vasilenko) and *Plectina cenomana* Carter & Hart.

The rich planktonic fauna is dominated by the *Hedbergella delrioensis* (Carsey) – *H. infracretacea* (Glaessner) – *H. brittonensis* (Loeblich & Tappan) plexus. The high-spired form *H. brittonensis* (= *Whiteinella brittonensis* of many authors e.g. Robaszynski & Caron 1979) is characteristic of the Cenomanian (Carter & Hart 1977) and the small high-spired form *H. infracretacea* of the Albian (Carter, Hart 1977; Price 1977a). The assemblage also cludes the small but distinctive *H. planispira* ppan), which ranges throughout most of the late arly Cretaceous in north-west Europe (Bartenstein 965; Carter & Hart 1977; Hart *et al.* 1981; Price 977a). This species is present in association with *Globigerinelloides bentonensis* (Morrow) which, when present in abundance, is an important index species for the Late Albian in north-west Europe (Hart 1973) and he North Sea (Burnhill & Ramsey 1981; Crittenden 984a). However, it is also known from the Cenomanian (Carter & Hart 1977; Hart *et al.* 1981).

5.3. Ostracoda

A sparse, poorly preserved fauna was recovered from this unit. The lowest sample, from a depth of 64.78-64.88 m, contains fragments tentatively assigned to *Protocythere albae* Damotte & Grosdidier. This species evolves into *Protocythere lineata striata* Gründel in the highest part of the *E. loricatus* Zone of the Gault in Eastern England (Wilkinson & Morter 1981) and its first occurrence in northern Germany is at the base of the *E. lautus* Zone (Bertram & Kemper 1971). In the present borehole, *P. lineata striata* was not found below 63.55-63.66 m. The presence of *Cornicythereis gatyensis* (Damotte & Grosdidier), *Isocythereis fissicostis fissicostis* Triebel, *Eucytherura rectangulata* Kaye and the absence of *Cythereis* (*Rehacythereis*) *luermannae* s.l. suggests that this sample can be assigned to the Middle Albian, but is older than the *E. meandrinus* (ammonite) Subzone.

Cythereis (*Rehacythereis*) *luermanni luermanni* Triebel was recovered from 63.94-64.04 m associated with *Saxocythere notera senilis* Kemper. This association first occurs in the *E. meandrinus* Subzone of East Anglia and extends up into the *H. orbignyi* (ammonite) Subzone (the basal part of the *M. inflatum* Zone) Wilkinson & Morter 1981), but in Germany this combination of species is used to recognise the *E. lautus* Zone (Bertram & Kemper 1971).

A single, weakly reticulate specimen intermediate between *Cythereis* (*R.*) *luermannae luermannae* and *C.*(*R.*) *luermannae hannoverana* Bertram and Kemper was recovered from a depth of 63.05-63.12 m. However, true *C.*(*R.*) *luermannae hannoverana* (with a well-formed reticulate ornament) was recovered above 62.50 m and is used to recognise the upper part of the *H. varicosum* to the lower part of the *M. rostratum* Subzones based on its distribution in East Anglia (Wilkinson & Morter 1981) and in north-west Germany (Bertram & Kemper 1971).

A single chalk-encrusted juvenile tentatively assigned to *C.*(*R.*) *bemerodensis* was found at a depth of 58.90 m and *C.*(*R.*) *luermannae hannoverana* and *Isocythereis fissicostis* were found only below 61.44 m. On this basis the highest part of the red chalk is no older than the uppermost part of the *S. dispar* (ammonite) Zone (highest Albian) and may be of Cenomanian age (cf. Bertram & Kemper 1971).

6. WHITE CHALK

(c.18.0-58.45 m)

6.1. Lithology

A detailed description of the lithostratigraphy of the white chalk sequence (including the Black Band) is in preparation and will not be discussed here. The unit comprises white to brownish white, argillaceous and nodular chalks. Flints are common in the chalk above the Black Band but are absent in the more argillaceous sequence beneath. Core recovery was in general poor owing to the comparatively soft nature of the chalk.

6.2. Foraminifera (P. J. Bigg, personal communication 1982)

Foraminifera recovered from the chalk sequence above the Black Band were poorly preserved and it would appear that recrystallisation has destroyed much of the microfauna. Close above the Black Band, *Hedbergella*

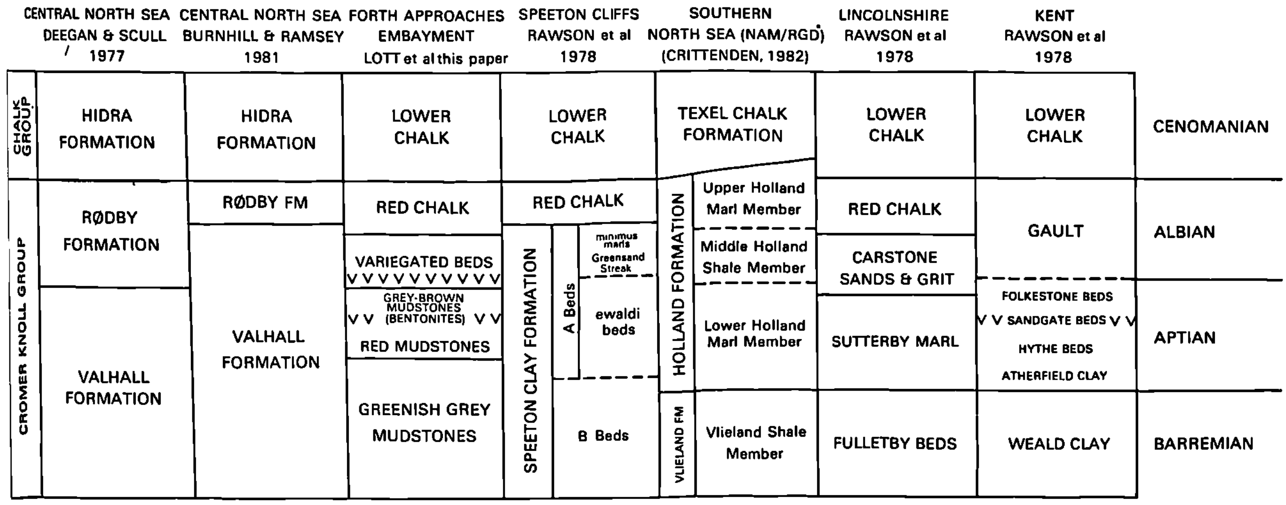

Fig. 7. Lithostratigraphic correlation of the mid-Cretaceous of onshore eastern England and the North Sea Basin.
(* NAM/RGD: Nederlandse Aardolie Maatschappij & Rijks Geologische Dienst 1980.)

brittonensis, *Praeglobotruncana stephani* (Gandolfi) and *Gavelinopsis berthelini* (Keller) are moderately common and *Dicarinella hagni* (Scheibnerova) and other planktonic species are well represented. The assemblage is typical of the *Whiteinella archaeocretacea* Zone which straddles the Cenomanian-Turonian boundary (Robaszynski & Caron 1979).

Sample preparations from the Black Band yielded phosphatic organic debris and some carbonised plant tissue, but no foraminifera. Hart and Bigg (1981) found a highly impoverished, exclusively agglutinated microfauna in the Black Band of Humberside, eastern England, but cuttings samples from the Central North Sea yielded planktonic foraminifera (Burnhill & Ramsey 1981). However, it appears probable that in the latter case the planktonic specimens are likely to have been derived by caving from the overlying marls and chalks.

Sample preparations from the argillaceous chalks below the Black Band yielded a rich microfauna dominated by planktonic forms. *Hedbergella delrioensis* is common, and *H. simplex* (Morrow) and *H. brittonensis* and the benthonic species *Lingulogavelinella umbilicitecta* (Fuchs) are fairly common. Also present are the keeled planktonics *Rotalipora cushmani* (Morrow) and *R. deeckei* (Franke). These assemblages suggest a Cenomanian age.

6.3. Ostracoda

This interval was not examined for Ostracoda.

7. DISCUSSION

Borehole 81/40 was sited, using shallow seismic profiles, on gently eastward-dipping Cretaceous strata in the Forth Approaches Embayment (Stoker 1984). In consequence, the sequence cored in Borehole 81/40 should prove to be more complete and representative of the basinal areas than many commercial wells sited on positive anticlinal or fault-controlled structures.

Early Cretaceous sedimentation in the North Sea Basin was characterised by the deposition of thick clay sequences which range in age from Ryazanian to Aptian and which are generally assigned to the Speeton Clay Formation of the Cromer Knoll Group (Rhys 1974; Deegan & Scull 1977). Deposition took place mostly in quiet-water marine environments, producing monotonous clay sequences in which the major lithological variations are the result of subtle changes in carbonate content. These changes appear to reflect an increase or decrease in abundance (and diversity) of microfaunal and microfloral assemblages as the sea transgressed and regressed across the basin, improving or inhibiting circulation, and therefore oxygenation, of the basin waters.

The oldest sediments encountered in borehole 81/40 are of Early Aptian to Barremian age. According to the ostracod faunas, the basal 12 m of the greenish-grey mudstones are Barremian, whereas according to the foraminifera they are Early Aptian. It is not possible resolve this discrepancy on the information obtain from this borehole alone. One possible explanation that the borehole sequence is more complete than tho of onshore north-west Europe, so that individual speci could range beyond their known stratigraphical limit

The upward incoming of coccolith-rich mar limestones at 99.94 m (Dr A. W. Medd pers. comn 1983), with abundant and diverse microfaun assemblages, in undoubted Early Aptian sediment provide a further indication of improving circulation i the basin as the transgression progressed. The occurenc of limestone developments is a characteristic feature c the Early Aptian of the North Sea Basin (Rawson & Riley 1982). By Mid to Late Aptian times, a renewe marine influx into the basin is indicated by the sudde proliferation of the planktonic foraminifer *Hedbergell infracretacea*. In the borehole sequence, it is notable tha the incoming of this planktonic species is also coincider with the change to reddened calcareous mudston lithologies. The abrupt colour change and reddening c both the Late Aptian mudstones and the Mid Albian t Early Cenomanian chalk is widespread throughout th North Sea area, and occurs not only in condense sequences over the more positive areas but also in th sequences between the highs. In both instances th reddening appears to be associated with transgressi phases, suggesting that increased oxygenation of th bottom waters may in part be responsible for th retention of an original red coloration of the sedimen and indicating a shallow-water depositiona environment (Jeans 1980; Gallois & Morter 1982).

Conformably overlying the red mudstones, the late Aptian sediments in the borehole comprise brown-gre mudstones with interbedded bentonites, the volcan origin of which is indicated by the presence of sanidi feldspar and biotite. Further work on the mineralogy o these bentonitic horizons is in progress (Knox, i preparation). The mudstones have yielded microfaun assemblages which suggest a *P. nutfieldiensis* Zon (Late Aptian) age. Widespread volcanic activity apparent at this level in the Late Aptian througho much of the north-west European area, and volcan sediments have been described from this Zone both i southern England (Sandgate Beds at Folkestone, Jean *et al.* 1982) and in Germany (Sarstedt & Thiede Zimmerle 1979). It is interesting to note that at Speeto cliffs bentonitic horizons have not yet been describe from the Aptian-Albian sequences. However, it is wort noting that the common association of these bentoniti horizons with vivid green 'glauconitic' streaks an patches in both this borehole and in the Germa succession may be mirrored at Speeton, where gree glauconitic bands and streaks have also been describe from the clay sequence immediately below the Lat Albian Red Chalk (Lamplugh 1899; Kaye 1965). Poo exposure of this part of the sequence at Speeton cliffs a present precludes confirmation of bentonitic bands a this level.

The source of the volcanic material, which is largely acidic to intermediate in composition, has been suggested as a site either in the southern North Sea area or in the western English Channel and South West Approaches (Jeans *et al.* 1982). These Late Aptian to Early Albian bentonites are the product of one of two important phases of Lower Cretaceous volcanic activity in the north-west European area, the other occurring in the Berriasian (Knox & Fletcher 1982; Zimmerle 1979) and coinciding with increasing tectonism at the plate margins to the west of Britain, associated with the opening of the Rockall Trough and rotation of the Iberian peninsula (Anderton *et al.* 1979).

On foraminiferal grounds, the Aptian/Albian boundary in the borehole sequence lies just below the marked unconformity that separates the grey-brown mudstone from the overlying variegated beds. The topmost part of the grey-brown mudstone unit is, however, strongly bioturbated and it is certainly possible that the erosion surface may represent the true Aptian/Albian stage boundary in the borehole, and that reworking during the early Albian transgression is responsible for any discrepancy between the biostratigraphical and lithostratigraphical boundaries.

The Early Albian transgression, characterised initially by extremely impoverished microfaunas and floras, is well documented in the European basin (Price 1977a). In the borehole sequence, the early Albian interval comprises a thin but extremely distinctive sequence of variegated clays and silts which contain a microfauna restricted to agglutinating foraminifera; no ostracods or coccoliths have been recorded. Within this variegated sequence a single bentonite horizon suggests a continuation of sporadic volcanic activity into the Early Albian. The transition to the overlying red chalk sediments is associated with the basin-wide Mid-Albian transgression.

The 'red chalk' in the borehole ranges from Mid Albian to Early Cenomanian in age. The sequence does not show the marked nodular development characteristic of much of the red chalk sequence at outcrop in Yorkshire and Lincolnshire and comprises largely uniform red chalk sediments. The transition to white chalk sedimentation occurs during the Early Cenomanian, with the development of argillaceous white chalk sediments. A thin black clay, the Black Band, forms a widespread marker close to the Cenomanian-Turonian boundary throughout much of the North Sea Basin (Hart & Bigg 1981) before a return to more normal white chalk sedimentation during the Turonian.

Acknowledgements. A large number of BGS staff were involved in the seagoing operations during the drilling of the borehole and their efforts are gratefully acknowledged. The borehole was funded by the Department of Energy. Dr Martyn Stoker must take credit for the siting of the borehole and for drawing our attention to the importance of the sequence. We would also like to thank Steve Crittenden (Gearhart Data Services Ltd) for his comments on the foraminifera text and Dr Beris Cox for her invaluable help in the preparation of some of the figures. The authors would like to thank the referees for their helpful and constructive comments. The paper is published with the permission of the Director, British Geological Survey (NERC).

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The stratigraphy of the Lower Cretaceous Speeton Clay Formation, from a cored borehole off the coast of north-east England

G. K. Lott, B. N. Fletcher and I. P. Wilkinson

Summary:

A fully cored stratigraphical borehole in the Southern North Sea Basin at 54° 39'N, 0° 14'E encountered a succession of Lower Cretaceous clays and mudstones, representing part of the Speeton Clay Formation of the Cromer Knoll Group, resting on Upper Jurassic Kimmeridge Clay.

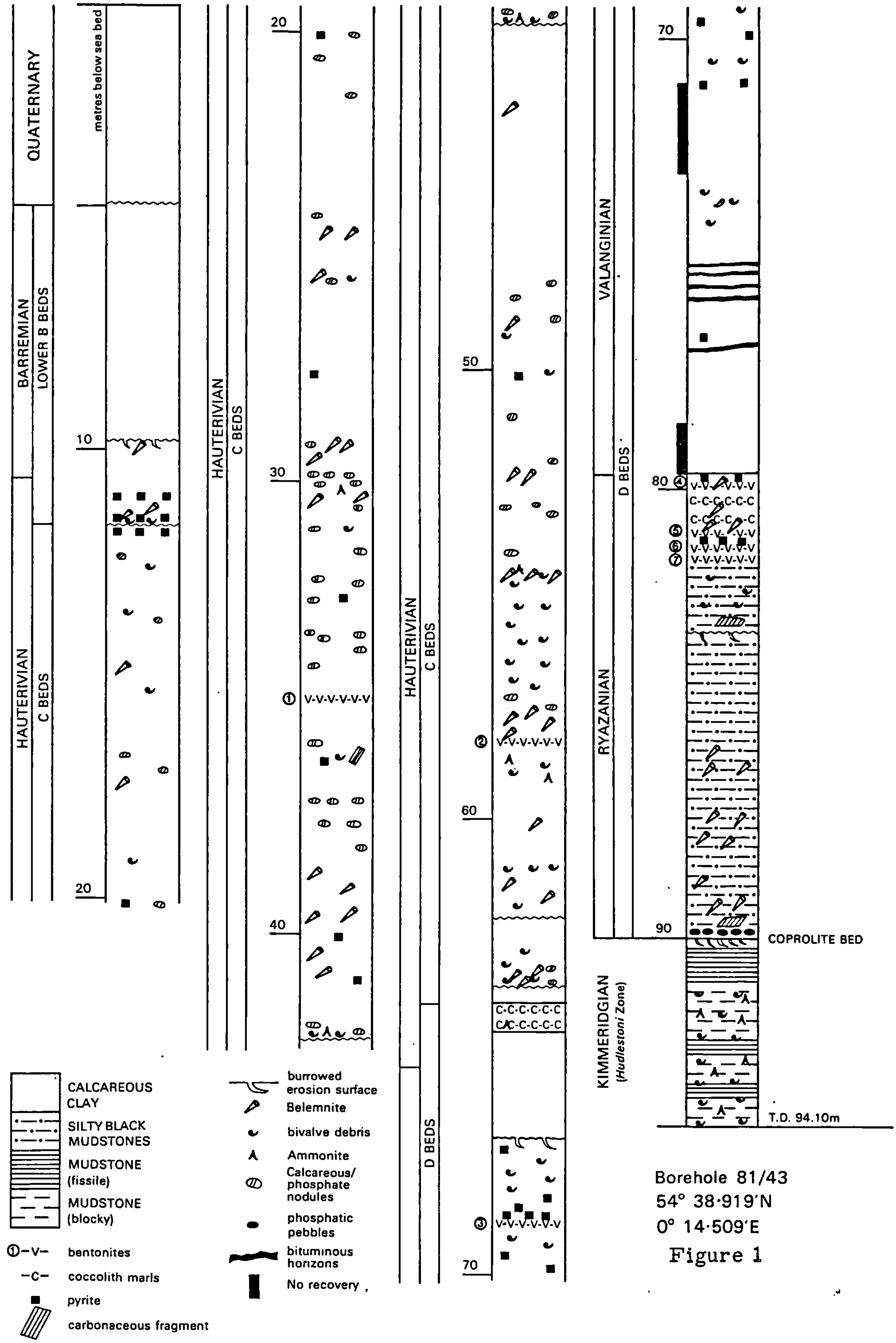
The Lower Cretaceous beds comprise c.90m of marine clays ranging from Ryazanian to Barremian (equivalent to beds D8 - LB6 at Speeton) and include seven thin bentonite horizons. The three uppermost bentonite horizons lie within the Valanginian to Hauterivian, an interval from which no bentonites have previously been recorded in the European area. Six of the seven bentonite horizons recorded in the borehole have now been recognised in the type section at Speeton, Yorkshire.

The borehole succession yielded rich microfaunal assemblages, which have enabled a detailed correlation to be made with the beds of the type locality at Speeton. The sequence cored in the borehole demonstrates a remarkable similarity to the Speeton sequence, despite an 80-kilometre separation of the localities.

Introduction

The Speeton Clay Formation (Rawson et al. 1978) of north-east Yorkshire is known to extend offshore into the southern North Sea Basin (Rhys 1974) and has been proved, but not cored, in a number of offshore commercial wells in the southern part of Quadrant 42, (Fig. 2) (Dingle 1971; Rhys 1974; Kent 1980; Rawson & Riley 1982).

During 1980/81 the British Geological Survey (BGS), funded by the Department


QUATERNARY
BARREMIAN
LOWER B BEDS
HAUTERIVIAN
C BEDS
D BEDS
VALANGINIAN
RYAZANIAN
KIMMERIDGIAN
(Hudlestoni Zone)
metres below sea bed
10
20
30
40
50
60
70
80
90
V-V-V-V-V-V
C-C-C-C-C-C
COPROLITE BED
T.D. 94.10m
CALCAREOUS CLAY
SILTY BLACK MUDSTONES
MUDSTONE (fissile)
MUDSTONE (blocky)
bentonites
coccolith marls
pyrite
carbonaceous fragment
burrowed erosion surface
Belemnite
bivalve debris
Ammonite
Calcareous/ phosphate nodules
phosphatic pebbles
bituminous horizons
No recovery
Borehole 81/43
54° 38·919'N
0° 14·509'E
Figure 1

of Energy, undertook a detailed shallow seismic survey of the southern North Sea area as part of its offshore regional mapping programme. In order to aid the interpretation of these seismic data, shallow cored boreholes were drilled in selected parts of the Mesozoic and Tertiary sequences of the basin.

One of these boreholes, BGS 81/43 (54°38. 919'N, 0°14. 509'E), was drilled 80 km ENE of Speeton cliffs in Block 42/12; it fully cored 89.87m of dark greenish grey, calcareous clays and brownish black, occasionally organic - rich and non-calcareous mudstones of Lower Cretaceous age (Speeton Clay Formation). These clays rest on 4.23m of dark olive-grey mudstones of Jurassic age (Fig.1).

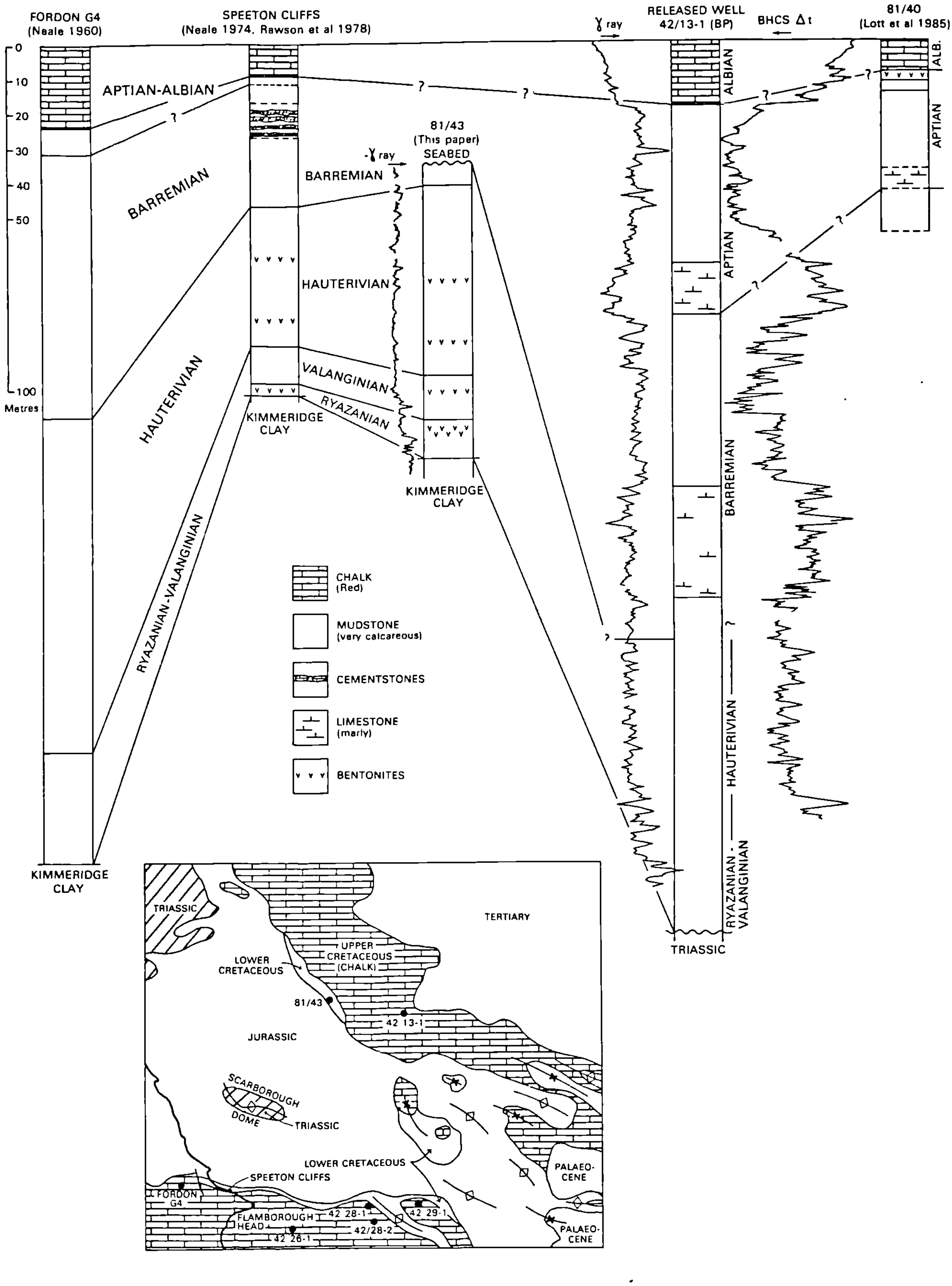
A comparison of the microfaunas of this offshore Lower Cretaceous sequence with those at the type section of the Speeton Clay in Filey Bay, Yorkshire, has shown that these marine clays range from Ryazanian to Barremian. The clays compare closely, both lithologically and sedimentologically, with the type section, and present a unique opportunity to establish the Lower Cretaceous stratigraphy offshore without the complications presented in the Speeton cliffs by landslipping, weathering and intermittent exposure.

The stratigraphy of the borehole presented here is based upon detailed examination of the foraminifera (B. N. Fletcher) and ostracoda (I.P.Wilkinson). The macrofossils of the Jurassic mudstones were identified by Dr B.M.Cox and the sedimentology of the sequence has been studied by G.K.Lott.

1. Stratigraphy and borehole sequence

The Speeton Clay Formation, which crops out on the North Yorkshire coast, is the most complete representative of marine Lower Cretaceous strata known onshore in Britain. The sequence is generally taken as the stratotype for the marine Boreal Lower Cretaceous of Europe.

The classic paper on the Speeton Clay is that by Lamplugh (1889), who divided the clays into five units (A, B, C, D and E downwards) on the basis of their belemnite faunas and, in the case of unit E (the basal Coprolite Bed), on its distinctive lithology. Subsequent work has resulted in a refined division of
five
these ~~5~~ basic divisions (Neale 1960, 1962; Kaye 1964; Fletcher 1969, 1973;



FORDON G4
(Neale 1960)
SPEETON CLIFFS
(Neale 1974, Rawson et al 1978)
γ ray
RELEASED WELL
42/13-1 (BP)
BHCS Δt
81/40
(Lott et al 1985)
0
10
20
30
40
50
100
Metres
APTIAN-ALBIAN
BARREMIAN
HAUTERIVIAN
RYAZANIAN-VALANGINIAN
KIMMERIDGE CLAY
81/43
(This paper)
SEABED
-γ ray
BARREMIAN
HAUTERIVIAN
VALANGINIAN
RYAZANIAN
KIMMERIDGE CLAY
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
RYAZANIAN - VALANGINIAN
TRIASSIC
ALB.
APTIAN
CHALK
(Red)
MUDSTONE
(very calcareous)
CEMENTSTONES
LIMESTONE
(marly)
BENTONITES
TRIASSIC
TERTIARY
UPPER CRETACEOUS
(CHALK)
LOWER CRETACEOUS
81/43
42 13-1
JURASSIC
SCARBOROUGH DOME
TRIASSIC
LOWER CRETACEOUS
PALAEO-CENE
SPEETON CLIFFS
FORDON G4
FLAMBOROUGH HEAD
42 28-1
42/28-2
42 29-1
PALAEO-CENE

Figure 2

Rawson 1971; Rawson & Mutterlose 1983).

In borehole 81/43 representatives of the B, C, D and E beds of the Speeton Cliff succession have been cored and a detailed examination has enabled many of the minor subdivisions known at Speeton to be recognised.

In addition to the extremely good biostratigraphical control of the sequence, a number of distinct lithological markers can be distinguished in the borehole and are used to demonstrate further correlations between the two sequences. These marker horizons include seven thin bentonites and a number of coccolith-rich limestone bands, most of which have recognisablable representatives in the onshore succession. The borehole was drilled using the chartered drilling ship m. v. Mariner, in a water depth of 67m, and obtained core of 0.10m (4 inch) diameter.

The borehole penetrated 4.50 metres of seabed sand before entering the Speeton Clay Formation and terminated at 94.10m in Kimmeridge Clay. All depths are measured from the seabed. The borehole was subsequently sub-sampled at approximately 0.5m intervals for micropalaeontological examination (Appendix 1).

Shallow seismic profiles across the Kimmeridge Clay / Speeton Clay boundary show a low-angle unconformity separating the two formations.

2. Jurassic: Kimmeridge Clay Formation

Upper Kimmeridgian 89.87-94.10m (the borehole Terminal Depth - TD.)

The oldest strata penetrated in the borehole consist of 4.23m of pale olive to brownish black, bituminous mudstones of Late Jurassic age. The upper 0.39m of these beds are dark, friable calcareous mudstones, cross-cut by a number of thin calcite - filled fractures and penetrated by large vertical burrows, 150-200mm in length, which pipe down small shiny phosphatic pebbles from the overlying Coprolite Bed. The faunal assemblage is indicative of the _Hudlestoni_ Zone , _Reisiformis_ Subzone of the Upper Kimmeridgian; it includes the ammonites _Pectinatites_ (_Virgatosphinctoides_) cf. _donovani_ Cope and _P._ (_V._) cf. _reisiformis_ Cope. The Kimmeridgian probably falls in Beds 42-44 of the standard Kimmeridge Clay sequence (Cox & Gallois 1979, 1981) (Dr B.M.Cox, pers. comm.

1984).

In the Speeton cliffs the Kimmeridgian mudstones are exposed, from time to time, at beach level. These beds belong to the Pectinatus Zone, Eastlecottenensis Subzone (Cope 1974) and are thus younger than the Kimmeridge Clay in the borehole, indicating the unconformable nature of the Coprolite Bed and the presence of an important stratigraphic break at this level.

3. Cretaceous: Speeton Clay Formation.

3.1. The Coprolite Bed (Bed E) 89.75-89.87m

The base of the Cretaceous sediments in the borehole is marked by a thin phosphatic conglomerate, the Coprolite Bed (0.12m). This grey, hard conglomeratic unit consists of angular clasts of olive-grey calcareous mudstone (possibly derived from the underlying Kimmeridge Clay) together with black, shiny , phosphatic subrounded pebbles, pyrite, and belemnite fragments in a non-calcareous muddy matrix. The phosphate pebbles range up to 0.01m across and show a distinctive polished, black patina; similar granule-sized grains also occur some distance above the top of the Coprolite Bed.

At the base of the unit there is a thin black clay 0.01m thick, packed with shiny, black phosphatic granules. The top of the unit is sharply defined erosion surface. At Speeton the Coprolite Bed is "a thin stony band of black phosphatised nodules" (Lamplugh 1889). It averages 0.10m in thickness and contains "numbers of black phosphatic pebbles . . . . caked together in a matrix" (Lamplugh, op cit.). In the coastal sequence the phosphatic nodules have yielded indeterminate ammonites (Rawson et al. 1978); however, in the borehole the Coprolite Bed contained only rare belemnite fragments. The Coprolite Bed has previously been described only from Speeton and the close similarity in both thickness and lithology of the bed in the offshore borehole 80km away, is remarkable.

3.2. Laminated mudstones and siltstones 82.99-89.57m.

These strata immediately overlie the Coprolite Bed and consist of hard, non-calcareous, dark grey to black, bituminous mudstones with thin paler interbedded siltstones. When initially recovered, they were characterised by a strong bituminous smell. Pyritic and phosphatic nodules occur at the base of the unit, together with rare, small shiny phosphatic pebbles. The beds show rare burrows and are non-fissile despite their obvious fine lamination. Variations in silt content produce a subtle pale to dark colour-banding throughout the unit. The beds yielded a sparse fauna consisting of poorly preserved belemnites, fish debris, radiolarians and agglutinated foraminifera. The top of the unit is marked by a large phosphatic concretion and a significant concentration of silt and sand laminae. Above this boundary the sediments are markedly paler and non-bituminous although they remain non-calcareous and silty.

At Speeton these black bituminous mudstones and siltstones are represented by a thin (0. 30m) 'Black Shale' unit (Bed D8) immediately overlying the Coprolite Bed (Neale 1962, 1974). Though considerably thinner than their offshore equivalents they show a similar restricted fauna. Attention has been drawn by Neale (1968) to the absence of bioturbation and consequent retention of the primary fine lamination of the unit at Speeton - a feature rare in the heavily burrow-mottled clays comprising the main part of the formation.

3.3. Calcareous clays 4.50-82.99m

The greater part of the cored Speeton Clay Formation consists of dark greenish grey, very calcareous non-fissile clays, closely comparable to the clays and mudstones at Speeton. The clays in the borehole are frequently silty, commonly with a gritty texture resulting from the profusion of foraminiferal tests and comminuted bioclastic debris that occur at various levels. Strong bioturbation is characteristic, with Chondrites-type burrow-mottling particularly common. Pale, cream-brown, calcareous and phosphatic nodules up to 0.03m in length with a dark brown rims are also common, especially between 30 and 40m, but they become rare below about 63m. Pyritic nodules are moderately abundant, with pyrite also occurring as small euhedral crystals, thin tubular burrowfills and framboids and, more rarely, in association with carbonised woody fragments. Glauconite and siderite are also common constituents of the clays. Belemnites are found at many levels; bivalve and ammonite fragments occur more rarely. Dr P.F.Rawson (pers. comm. 1984) identified a slightly phosphatised ammonite fragment at 64.46m as Karakaschiceras heteroptychum (Pavlow); he further states that this species is known in the phosphatic nodules of the early Valanginian bed D2D at Speeton, along with other remanie fossils. The genus Karakaschiceras appears limited to the latest early Valanginian and earliest late Valanginian time interval, in both the Tethyan region and North-West Europe. Flattened inner whorls of Aegocrioceras cf. quadratum (Crick) were identified (P. F. R.) at 57.12m. This ammonite is found in beds C7F and C7G at Speeton. A single thin densely phosphatised vertebra was found at 58.71m. At several horizons, notably at 64.07 - 64.46m, 80.28 - 80.36m and 80.66 - 80.72m, pale grey to white, burrow-mottled soft marly limestones are thinly developed. These beds represent extremely rich concentrations of coccoliths (Dr A.W.Medd pers. comm. 1983) and may correlate with similar coccolith blooms recognised in the Speeton cliffs sequence (Black 1971). They probably account in part for variations in carbonate content throughout the sequence, and hence for the subtle pale to dark colour-banding apparent at some levels.

The light grey calcareous marl unit at 64.07 - 64.46m can, on the basis of the foraminifera and ostracoda, be equated with the uppermost D beds (D1-D2D), and is thought to be a correlative of the Compound Nodular Bed (D1), an important marker horizon in the coastal sequence, which Black (1971) noted was particularly rich in coccoliths.

The seven bentonite bands recorded in the borehole lie within this calcareous clay sequence. The thin bluish grey bentonites commonly show burrow-mottling but still retain sharp tops and bases. The lowest group of four bentonites (4-7) can be correlated, by means of their associated foraminiferal assemblages, with those recognised within the lower D beds (Ryazanian) at Speeton (Knox & Fletcher 1978). The three upper bentonite horizons are essentially the same in lithology and composition as the lower group.

The foraminiferal assemblages associated with bentonite 1 include Hechtina antiqua Reuss and Frondicularia simplicissima Dam, and this bed equates with the upper C4 beds (late Hauterivian) at Speeton. The assemblages above and below bentonite 2 are composed of long-ranging foraminifera and are diagnostic only of an early Hauterivian age. Conorboides valendisensis Bartenstein & Brand , Ammobaculites subcretaceus Cushman & Alexander, Ammodiscus tenuissimus (Guembel) and Glomospira gordialis (Jones & Parker) associated with the adjacent beds of bentonite 3, suggests a correlation with the upper D4 beds (Valanginian) at Speeton.Two of these bands (bentonites 1 and 2) have subsequently been recognised in the Speeton sequence (Fig. 2) (Dr R.W.O'B. Knox pers. comm. 1983).

These bentonite horizons provide good marker horizons and should prove useful for correlation across the North Sea Basin. The bentonites of Ryazanian age at Speeton and in the borehole probably correlate with tuffs of similar age in the Schuttorf 3 borehole near Bentheim, North West Germany (Zimmerle 1978). More detailed work on the mineralogy and stratigraphic relationship of these bentonites with other Lower Cretaceous volcanic units is being carried out by Dr R. W. O'B. Knox.

4. Foraminifera

The basal Cretaceous unit, with its dark silty mudstones and phosphatic material, yeilded a very restricted but distinctive microfauna of mainly crushed and distorted Haplophragmoides cf. concavus (Chapman) (Fig.4S), together with Ammobaculites subcretaceous Chapman & Alexander and Verneuiinoides neocomiensis (Mjatliuk) (Fig.4Q) (samples 83.20-89.75m). These basal mudstones accumulated under restricted marine conditions and their distinctive fauna of arenaceous benthonic foraminifera enable them to be correlated with the D8 beds (Ryazanian) on the Yorkshire coast. In the borehole D8 is 6.58m thick compared with 0.30m on the coast. The bentonite bands that form beds D6E, D6J, D7D and D7F at Speeton are clearly seen in the borehole. A useful index species, Lenticulina (S.) valanginiana (Bartenstein & Brand), occurs for the first time in the borehole just below the lowest bentonite band (equivalent to bed D7F) in sample

81.70-81.85m, and is also found in some of the beds between the other bentonite bands. At Speeton it is found in the upper part of the D7 beds and in the D6 beds and has a range of Ryazanian to early Valanginian. Just beneath the uppermost of these four bentonites (equivalent to bed D6E), Citharina pseudostriatula Bartenstein & Brand, L. (S.) valanginiana, L. (M.) striatocostata (Reuss) and Nodosaria sceptrum Reuss (Fig.4K) occur. C. pseudostriatula, a species which at Speeton is virtually confined to the D6 beds (Fletcher 1973), is found in large numbers in sample 80.25 - 80.38m, and the unit seems to be a likely correlative of the D6 beds.

The beds overlying this unit are sparsely fossiliferous and, on this basis, a correlation with the similarly sparsely fossiliferous D5 beds at Speeton is suggested. The Ryazanian / Valanginian stage boundary is placed at the junction of the D5/D4 beds at Speeton (Rawson et al. 1978), and in the borehole the stage boundary is therefore placed at c.79.70m, i.e. at the top of the sparsely fossiliferous unit.

Ammovertella cellensis (Bartenstein & Brand), a species which makes its first appearance at Speeton in the upper D5 beds, is first recorded at 77.70-77.80m in the borehole. Epistomina caracolla (Roemer) (Fig.3G,H) (sample 75.17-75.25m), Pseudonodorosaria humilis (Roemer) (Fig.4L) (69.76-69.84m), Frondicularia concinna (Koch) (Fig.4F) and Lenticulina saxonica (Bartenstein) (Fig.3D) (66.84-66.92m) together with an abundance of Conorboides valendisensis (Bartenstein & Brand) (71.10-71.20m) suggest a correlation with the high D4 beds (Valanginian) at Speeton, equivalent to the Platylenticeras Beds. At Speeton late Valanginian sediments are represented only by a regressive remanie deposit (D2D) at the base of the Hauterivian, containing derived late Valanginian ammonites. The Valanginian / Hauterivian boundary is distinguished therefore, in the Speeton section by a marked faunal change over at the top of bed D2E. In the borehole the first Hauterivian foraminiferal assemblages are seen in sample 66.92 - 67.06m. The stage boundary is therefore placed at an erosion surface at c.67m (equivalent to the base of bed D2D at Speeton), and consequently has been placed lower in the sequence than suggested by the limited ammonite evidence.

The basal part of the Hauterivian, with a rich microfauna compared to that of the underlying Valanginian beds, contains numerous typically Hauterivian forms, including Vaginulina arguta Reuss and Frondicularia hastata Roemer (Fig.7G) and Lenticulina (M.) foeda (Reuss) (Fig.4H) in samples at 66.84 - 66.92m, and Vaginulina kochi Roemer (Fig.4C), Lenticulina ouachensis wisselmanni (Bettenstaedt) (Fig.3B,C), L. eichenbergi Bartenstein & Brand (Fig.3A) and L. crepidularis (Roemer)at 66.24-66.32m.

The Endemoceras regale ammonite Zone at Speeton can be recognised in the borehole by the first occurrence of Marsonella kummi Zedler (Fig.4R) in samples at 66.24 - 66.32m, Textularia foeda (Reuss) (60.78 - 60.86m), Epistomina ornata (Roemer) (Fig.4 E,F), Citharina harpa (Roemer) (Fig.4B) (58.47 - 58.53m) Vaginulina riedeli (Bartenstein & Brand) (53.61 - 53.68m) and Gaudryinella sherlocki (Bettenstaedt) (53.13 - 53.20m).The Simbirskites (Speetoniceras) inversus Zone at Speeton and in the borehole has a rich and varied fauna of foraminifera, but they are mostly long-ranging forms of little use for the precise definition of these beds. The first occurrence of Tritaxia pyramidata Reuss (Fig.4 I,J) (sample 26.75 - 26.78m) suggests correlation with the uppermost speetonensis or gottschei ammonite Zone at Speeton.

The incoming of Hechtina antiqua (Reuss) (Fig.3 M,N) in a sample at 34.56 - 34.63m, of Frondicularia simplicissima (Dam) (Fig.4 D,E) (32.28 - 32.86m) and Lamarckina (Pseudolamarckina) lamplughi (Sherlock) (Fig.3 J,K) (31.32 - 31.38m) indicates a correlation with the Simbirskites (Craspedodiscus) gottschei ammonite Zone, which forms the C4 beds at Speeton.

Between 41.63 and 9.98m the very small Conorboides sp. (Fig.4 M,N,O,P) occurs, locally in large numbers.

The first appearance of the valuable index species Gavelinella sigmoicosta (Dam) (Fig.3I) at 28.74 - 28.84m and Citharina acuminata (Ress) (Fig.4A) at 21.29 - 21.33m shows that this part of the borehole equates with the upper part of the Hauterivian Simbirskites (Simbirskites) marginatus Zone of bed C3 on the coast.

The base of the Simbirskites (Craspedodiscus) variabilis Zone (Bed C2C on the coast) is taken as the Hauterivian - Barremian boundary, but is difficult to recognise on foraminiferal evidence. The uppermost part of the borehole, above 8.57m, contains a poor microfauna, dominated in parts by Epistomina hechti (Bartenstein , Bettenstaedt and Bolli), indicating early Barremian beds belonging to the Hoplocrioceras fissicostatum and Paracrioceras elegans ammonite zones of beds LB1 at Speeton.

5.Ostracoda

The basal silty mudstones in the borehole contain only rare indeterminate fragments and moulds of ostracods, the only recognisable assemblage being found in samples at 80.25 - 80.38m. Here a fragmentary fauna with Cytheropterina trieteli Neale, Schuleridea juddi Neale and (?)Galliaecytheridea teres Neale is comparable with that described from the D6 beds (Perigrinoceras albidum Zone) of Speeton (Neale 1978).

The lowest Valanginian ostracod fauna was recorded at 74.00-74.10m and is placed in the Protocythere hannoverana ostracod Zone as defined by Christensen (1974). In Germany, P. hannoverana (Fig. 6A) Bartenstein ~~and~~ & Brand occurs in the upper part of the Platylenticeras Beds, throughout the Polyptichites Beds and in the basal part of the Dichotomites Beds (Bartenstein 1959). In England it has been recorded from the upper part of D4 to the top of bed D2E of Yorkshire (Neale 1962) and from the lower part of the Claxby Formation (Hundleby Clay and Claxby Ironstone members) of Lincolnshire (Wilkinson, unpublished data). In the borehole it is frequently found associated with Schuleridea praethoerenensis Bartenstein & Brand (Fig.6B) and Valendocythere pseudopropria (Bartenstein & Brand) (Fig.6C), although the last-named species has not yet been recorded from Speeton. The four subzones of the Protocythere hannoverana ostracod Zone as erected by Neale (1978) for Yorkshire could only be partially recognised. The Cytheropterina eboracica Subzone could not be substantiated since the only occurrence of the index species was at the same level as Paranotacythere (Paranotacythere) globosa globosa (Neale), the index species of the succeeding subzone. The interval 69.28 - 69.76m is tentatively placed in the P. globosa Subzone of Neale (1978), which onshore is found in D4B and the lower part of

D4A. Above, between 66.32 and 67.96m, Stravia crossata Neale,the subzonal index species for the upper part of D4A to basal part of D2E in Yorkshire, was recorded, although the highest of the Speeton subzones, based on the presence of Cytherella valanginiana Neale, could not be recognised.

Two other species recovered from the borehole are worthy of note. Cytherelloidea rehburgensis Bartenstein and Brand (Fig.5D) was described from the "Mittel-Valendis 2" to "Ober-valendis 2 " of northern Germany by Bartenstein (1959) and is also included in the species list of Ryazanian Ostracoda of Portugal (Rey et al. 1968). According to Neale (e.g. 1977,1984) this warm-water genus was unable to enter the "boreal" seas until the early Hauterivian. It is interesting therefore to note its presence in the Valanginian of borehole 81/43 (at 69.76 - 69.84m), although it occurred only as a single specimen (a single specimen has also been recovered from the Valanginian of the Skegness Borehole (Wilkinson, unpublished data). It may be, therefore, that links with Tethys had begun to develop during the early Valanginian. The other notable occurrence is Euryitycythere cf. subtilis Bartenstein & Brand (Fig.6E), recovered from the Valanginian/Hauterivian boundary interval of the borehole (66.84-66.92m). This Mesogean genus first evolved during the Berriasian in south-east France, spreading to north - west Germany in the Valanginian and, according to Donze (1973) and Neale (1962,1977), was unable to invade the "boreal" seas until the early Hauterivian.

As at Speeton there is no evidence of late Valanginian ostracod faunas in the borehole.

A marked faunal change takes place between 65.64 and 66.92m. At the base of this interval three early Valanginian species, Protocythere hannoverana, Protocythere pseudopropria and Schuleridea praethoerensis, form 58 per cent of the ostracod population. In the middle part (66.24-66.32m) these forms were not found, being replaced by the early Hauterivian species Mandocythere frankei frankei (Triebel) (Fig.5F), Haplocytheridea kummi (Triebel) (Fig.6G), Schuleridea lamplughi Neale (Fig.6H) and Schuleridea thoerenensis werlesis Grundel. Valanginian species were present(e.g. Stravia crossata and

Cytheropteron eboracica Neale), but these are considered to be reworked because of their state of preservation. At the top of the interval Valanginian Ostracoda were absent and the ostracod fauna is dominated by Mandocythere frankei frankei (56%), Schuleridea wendensis Neale (25%) and Eucytherura neocomiana Kaye (15%).

As at Speeton, both the ostracods and foraminifera confirm that late Valanginian sediments are absent from the borehole. The important faunal change in the foraminifera is close to a marked erosion surface at c.67m and some reworking of the Ostracoda appears likely since good Valanginian ostracod assemblages were noted up to 1 metre above this surface.

The presence of M. frankei frankei (Triebel) is significant, for it is the index species of the ostracod zone equating with the Endemoceras amblygonium and Endemoceras noricum zones onshore (Neale 1978). This species has been recorded from the late Valanginian of southern France (Donze 1976) and the Asterian Schichten of Germany (Kemper 1971), but in Britain it is a characteristic early Hauterivian form. Other species include Paranotacythere (P.) anglica Neale, restricted to the E. amblygonium and E. noricum zones in Yorkshire, and Dolocytheridea hilseana (Roemer), which is rare in the early Hauterivian of Speeton, although Grundel (1971) shows it to occur throughout the early Hauterivian in northern Germany, possibly having evolved in the late Valanginian. At 65.26 - 65.40m several species make their first appearance, including Cytherella fragilis Neale and Exophthalmocythere mamillata Triebel. This may indicate that it is possible to subdivide the M. frankei (ostracod) Zone , but the index forms used by Neale (1978), namely Euryitycythere parisiorum and Bythoceratina bispinata, were not found at this level.

Protocythere hechti Triebel (Fig.6I), Acrocythere hauteriviana (Bartenstein), Cytherelloidea ovata Weber, Cytherella exquisita Neale, Cytheropteron exquisita Kaye and Pseudomacrocypris parva (Kaye) all appear for the first time at 63.54 - 63.66m and continue in the succeeding sample at 62.34 - 62.42m with the first occurrence of Protocythere triplicata (Roemer). M. frankei frankei becomes extinct below 63.54 - 63.66m. It is believed that the E. noricum/E. regale zonal boundary can be placed at approximately 63.80m, i.e.

the base of the P. triplicata (ostracod) Zone as defined by Neale (1978).

Neale's (1978) P. triplicata ostracod Zone extends from the base of the E. regale Zone (bed C11) up into the middle part of the Barremian, the top being ill-defined. The study of assemblages from the borehole suggest that a more refined zonal scheme is possible. However, the zonation proposed here should be considered of local significance only, until more widespread investigations have been carried out. The suggested ostracod zonation for the borehole, based upon the earliest occurrence of the zonal species is:

3. Paranotacythere inversus costata / Cytherelloidea pulchra (ostracod) Zone (youngest)

2. Apatocythere simulans (ostracod) Zone

1. Paranotacythere (P.) diglypta (ostracod) Zone (oldest)

Bassiouni (1974) showed the usefulness of the genus Paranotacythere in biostratigraphical analyses. P. (P.) diglypta (Fig.6J), found no higher than 51.33 - 51.40m in the borehole, is only known from the early Hauterivian E. amblygonium - E. noricum zones at Speeton, but extends up into the E. regale Zone on the continent. In the late Hauterivian it apparently evolved into the P. inversum lineage, the earliest subspecies of which is Paranotacythere (P.) inversa costata (Kaye) (Fig.6K). This species is known to occur in beds C2 - C4 (S. marginatus and S. gottschei zones) in Yorkshire and is found in most samples between 12.72m and 36.95m in the borehole. It is associated with Cytherelloidea pulchra Neale (Fig.6L), which evolved from Cytherelloidea ovata Weber (Fig.6M), also found in bed C4 in Yorkshire. In Lincolnshire , Apatocythere simulans Triebel (Fig.6N) first evolved in the S. inversus Zone (Wilkinson unpublished data), although in Yorkshire its earliest record is in the Barremian and in Heligoland and Germany , the species has been found in the late Hauterivian (Bartenstein & ~~and~~ Oertli 1975). Its first occurrence, at 48.43-48.55m, is considered to mark the base of the _S. inversus_ Zone (bed C7). It is associated with _Metacytheropteron_ sp.(Fig.6O), rare _Chapmanicytherura nuda_ Kaye), _Dicrorygma speetonensis_ Christensen and _Cytheropteron reightonensis_ Kaye. _Acrocythere hauteriviana,_ which first evolved in the early Hauterivian, was not recovered between 39.18m and 59.76m, but reappeared at 38.63-38.70m and was consistently present throughout the remainder of the borehole. At Speeton a similar situation is apparent, the species being absent above bed C8, but present again in C4 (Neale 1971).

Paranotacythere (Paranotacythere) ramulosa ramulosa (Sharpova) (Fig.5Q) occuring between 11.74 and 36.32m in the borehole, is confined to the late Hauterivian of Germany (Bassiouni 1974). In Yorkshire it is characteristic of the faunas from the lower part of beds C2 and C3, the _S. marginatus_ Zone. _Schuleridea bilobata_ Triebel (Fig.6P), which also ranges throughout the late Hauterivian, was recorded above 22.67m in the borehole and appears to have a similar distribution in Fordon G1 Borehole, Yorkshire (Neale 1960).

The presence of _Paranotacythere (Paranotacythere) blanda_ (Kaye) at 11.05m indicates the Barremian, since this species is confined to the C2C - LB3 interval at Speeton (Kaye,1962;Neale 1978). The specimens recovered from the borehole were rare and fragmentary; nevertheless the Hauterivian / Barremian boundary is tentatively placed at about 11. 80m at a slight erosion surface. _Protocythere triplicata_, which ranges up to the top of the Cement Beds (B beds) of Yorkshire, was present below 9.80m in the borehole but, above this level, samples were barren of Ostracoda except for rare indeterminate fragments and decalcified moulds, and , at 5.03 - 5.07m, very rare juveniles of _Paranotacythere (Paranotacythere) inversa inversa_ (Cornuel). The last indicate an early to mid-Barremian age, but the diverse ostracod faunas of the late Barremian (Lott et al. 1985) were not seen.

6. Discussion

The depositional environment of the Speeton Clay Formation has been widely documented (e.g. Neale 1974 and Rawson *et al* 1978). The generally uniform sequence in the North Sea area represents the continuation from the late Jurassic of a long period of quiet-water marine clay sedimentation with little or no coarse clastic detritus entering the main basin. The depositional basin extended from eastern England into north-west Germany and northwards into the Central and Viking Grabens. It was bounded to the south by the London - Brabant High, a barrier apparently unbreached until the Aptian /Albian and separating the northern marine clay facies from the largely paralic 'Wealden' sediments of southern and western Britain (Allen 1981). The landmasses supplied little clastic material to this northern basin other than as local sands in the north Norfolk - East Midlands area (Spilsby Sandstone) and in the Moray Firth and Central Graben areas (Devil's Hole Fm.) (Anderton et al. 1979; Deegan and Scull 1977). The Speeton Clay Formation reaches a thickness of 350m in the Southern North Sea Basin but farther north (i.e. north of the Mid North Sea High) up to 793m have been recorded for the Cromer Knoll Group as a whole (Deegan & Scull 1977), significantly thicker than the type section in Yorkshire where the equivalent beds are 102m thick.

Initial deposition of the Speeton Clay, following a break in sedimentation during the late Jurassic - early Cretaceous, commenced with the accumulation of the thin transgressive remanie Coprolite Bed, consisting of phosphatised, rolled pebbles, fossil fragments and mudstone clasts, all largely derived from erosion of the underlying Kimmeridgian beds. Subsequent sedimentation is represented in the borehole by an 8m sequence of black non-calcareous, silty organic-rich mudstones, and at Speeton by 0.3 metres of black mudstones forming bed D8 (Neale 1974). The lithology of these basal mudstones is suggestive of a restricted marine environment with poor circulation and oxygenation.

Comparable developments of such organic-rich shales at the onset of a marine transgression have been documented from a number of Jurassic sequences (Hallam & Bradshaw 1979). It is notable that the area to the east and south-east of the borehole, in the Southern North Sea Basin, is characterised by large salt structures (Dingle 1971, Lott 1985) which were probably actively developing throughout the Lower Cretaceous and which may therefore have contributed to the restriction of circulation of the basin waters during the initial transgression by forming significant barriers. The fauna of these black mudstones is very limited comprising poorly preserved belemnites, agglutinating foraminifera, radiolarians and fish debris. The borehole sequence shows little evidence of bioturbation, suggesting a restricted benthic fauna. The absence of calcareous microfossils, however, could be attributable to later diagenetic effects; certainly the state of preservation of the belemnites in this lower sequence is very poor. The association of radiolarians with black shale sequences similar to this basal Speeton Clay has been documented by a number of authors (see Jenkyns 1980).

The deposition of these basal mudstones in the borehole is terminated by a break in sedimentation, demonstrated by the development of large phosphatic concretions at 83m (Fig.2), though no faunal change is seen at this level.

The sediments overlying the concretions are markedly calcareous and paler in colour, with only minor organic-rich horizons. A similar change is documented at this horizon at Speeton (Neale 1974). A rich benthonic microfauna and strong bioturbation is evident throughout the borehole sequence. The change in lithology appears to represent improved circulation and oxygenation and perhaps deeper water, however, quiet-water sedimentation continued.

The fine microfaunal subdivisions recognised in the lower part of the sequence, beds D7 to D1, at Speeton (Fletcher 1973; Neale 1974), can be correlated with those of the borehole with little difficulty and the thicknesses of individual units are similar. In particular the thin bentonite bands in the lower part of the borehole, within the Ryazanian sequence, can be correlated with those at Speeton (Knox & Fletcher 1979) and show remarkably little variation in thickness despite an 80km separation between the localities. Within these lower beds, which correlate with D1-D7E at the coast, sporadic thin white marls occur. These represent coccolith-rich 'blooms', which in the Kimmeridge Clay are closely associated with oil-shale horizons (Gallois 1976. Thin, sooty, bituminous horizons were noted in the core. Bioturbation of these white marls is very apparent, with dark Chondrites-type burrow-fills, mottling the pale calcareous matrix.

The dark calcareous clays that characterise the bulk of the disconformably overlying Hauterivian to Barremian in the borehole (C Beds - Lower B Beds) contain a rich microfauna. Lithological changes within this part of the sequence are restricted to subtle variations in carbonate content, and no major breaks in sedimentation are apparent, indicating a more stable regime of deposition. The thin bentonites point to continued spasmodic volcanic activity throughout the Hauterivian.

The thickness of the Speeton Clay Formation in the Southern North Sea Basin, is on the basis of released well data, very variable. Wells sited near the crests of some of the larger salt structures commonly show thin Lower Cretaceous successions, whereas those in the associated rim-synclinal troughs and along the north-west to south-east trending Dowsing Fault complex show much thicker sequences - 250m in B. P. Well 42/13-1. A comparison of the downhole Gamma Ray log of borehole 81/43 with that of released Well 42/13-1, which lies 25 km to the east, suggests that this expansion in thickness may be represented at least in part by the incoming of Barremian and Aptian sediments. Log correlations between the two boreholes suggest that c. 137m of Upper Barremian to Aptian sediments are present in Well 42/13-1, overlain by c.21m of Aptian - Albian red marls and red chalk. A suggested correlation between borehole 81/43 and the expanded Lower Cretaceous sequence in released B.P. well 42/13-1 is shown in Figure 2.

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Figure captions

Fig. 1. Summary log of the borehole.

Fig. 2. Borehole location and correlation with adjacent successions.

Fig. 3. Selected Ryazanian to Barremian Foraminifera from the Speeton Clay Formation of Borehole 81/43. (All material is deposited in the palaeontological collections of the British Geological Survey, Keyworth, Nottingham England).

Fig. 4. Selected Ryazanian to Barremian Foraminifera from the Speeton Clay

Formation of Borehole 81/43.

Fig. 5. Range chart of Valanginian - Barremian Ostracoda from Borehole 81/43.

Fig. 6. Valanginian - Barremian Ostracoda from the Speeton Clay Formation of Borehole 81/43. Magnification x75 unless otherwise stated. (All material is deposited in the palaeontological collections of the British Geological Survey, Keyworth, Nottingham, England.

Fig.3 Selected Ryazanian - Barremian foraminifera from the Speeton Clay Formation of borehole 81/43. All material is deposited in the palaeontological collections of the British Geological Survey, Keyworth, Nottingham, England.

A. Lenticulina (Lenticulina) eichenbergi Bartenstein & Brand 1951 MPK 5026 (ex CSB 4676) from 55.30-55.38m. x35.

B. Lenticulina (Lenticulina) ouachensis wisselmanni (Bettenstaedt 1952) MPK 5027 (ex CSB 4655) from 44.97-45.06m. x30.

C. Lenticulina (Lenticulina) ouachensis wisselmanni (Bettenstaedt 1952) MPK 5028 (ex CSB 4655) from 44.97-45.06m. x25.

D. Lenticulina (Lenticulina) saxonica Bartenstein & Brand 1951 MPK 5029 (ex CSB 4562) from 12.43-12.77m. x30.

E. Epistomina ornata (Roemer 1841) MPK 5030 (ex CSB 4676) from 55.30-55.38m. x50.

F. Epistomina ornata (Roemer 1841) MPK 5031 (ex CSB 4676) from 55.30-55.38m. x50.

G. Epistomina caracolla (Roemer 1841) MPK 5032 (ex CSB 4616) from 29.33-29.40m. x50.

H. Epistomina caracolla (Roemer 1841) MPK 5033 (ex CSB 4616) from 29.33-29.40m. x50.

I. Gavelinella sigmoicosta (Dam 1948) MPK 5034 (ex CSB 4562) from 12.43-12.77m. x60.

J. Gavelinella sigmoicosta (Dam 1948) MPK 5035 (ex CSB 4562) from 12.43-12.77m. x74.

K. Lamarckina lamplughi (Sherlock 1914) MPK 5036 (ex CSB 4616) from 24.33-29.40m. x74.

L. Lamarckina lamplughi (Sherlock 1914) MPK 5037 (ex CSB 4616) from 24.33-29.40m. x74.

M. Hechtina antiqua (Reuss 1863) MPK 5038 (ex CSB 4629) from 34.56-34.63m. x50.

N. Hechtina antiqua (Reuss 1863) MPK 5039 (ex CSB 4629) from 34.56-34.63m. x50.

Fig. 4 Selected Ryazanian - Barremian foraminifera from the Speeton Clay Formation of borehole 81/43. All material is deposited in the palaeontological collections of the British Geological Survey, Keyworth, Nottingham, England.

A. Citharina acuminata (Reuss 1863) MPK 5040 (ex CSB 4551) from 10.21-10.25m. x40.

B. Citharina harpa (Roemer 1841) MPK 5041 (ex CSB 4640) from 39.18-39.20m. x40.

C. Vaginulina kochi Roemer 1841 MPK 5042 (ex CSB 4664) from 49.16-49.25m. x25.

D. Frondicularia simplicissima Dam 1946 MPK 5043 (ex CSB 4604) from 49.16-49.25m. x65.

E. Frondicularia simplicissima Dam 1946 MPK 5044 (ex CSB 4604) from 49.16-49.25m. x65.

F. Frondicularia concinna Koch 1851 MPK 5045 (ex CSB 4589) from 21.09-21.13m. x40.

G. Frondicularia hastata Roemer 1842 MPK 5046 (ex CSB 4670) from 52.19-52.26m. x12.

H. Lenticulina (Marginulinopsis) foeda (Reuss 1863) MPK 5047 (ex CSB 4594) from 22.22-22.26m. x50.

I. Tritaxia pyramidata Reuss 1863 MPK 5048 (ex CSB 4608) from 26.75-26.78m. x60.

J. Tritaxia pyramidata Reuss 1863 MPK 5049 (ex CSB 4608) from 26.75-26.78m. x60.

K. Nodosaria sceptum Reuss 1863 MPK 5050 (ex.CSB 4610) from 27.27-27.30m. x60.

L. Pseudonodosaria humilis (Roemer 1841) MPK 5051 (ex CSB 4626) from 33.64-33.72m. x55.

M. Conorboides sp. MPK 5052 (ex CSB 4619) from 30.62-30.69m. x360.

N. _Conorboides_ sp. MPK 5053 (ex CSB 4630) from 34.92-35.00m. x360.

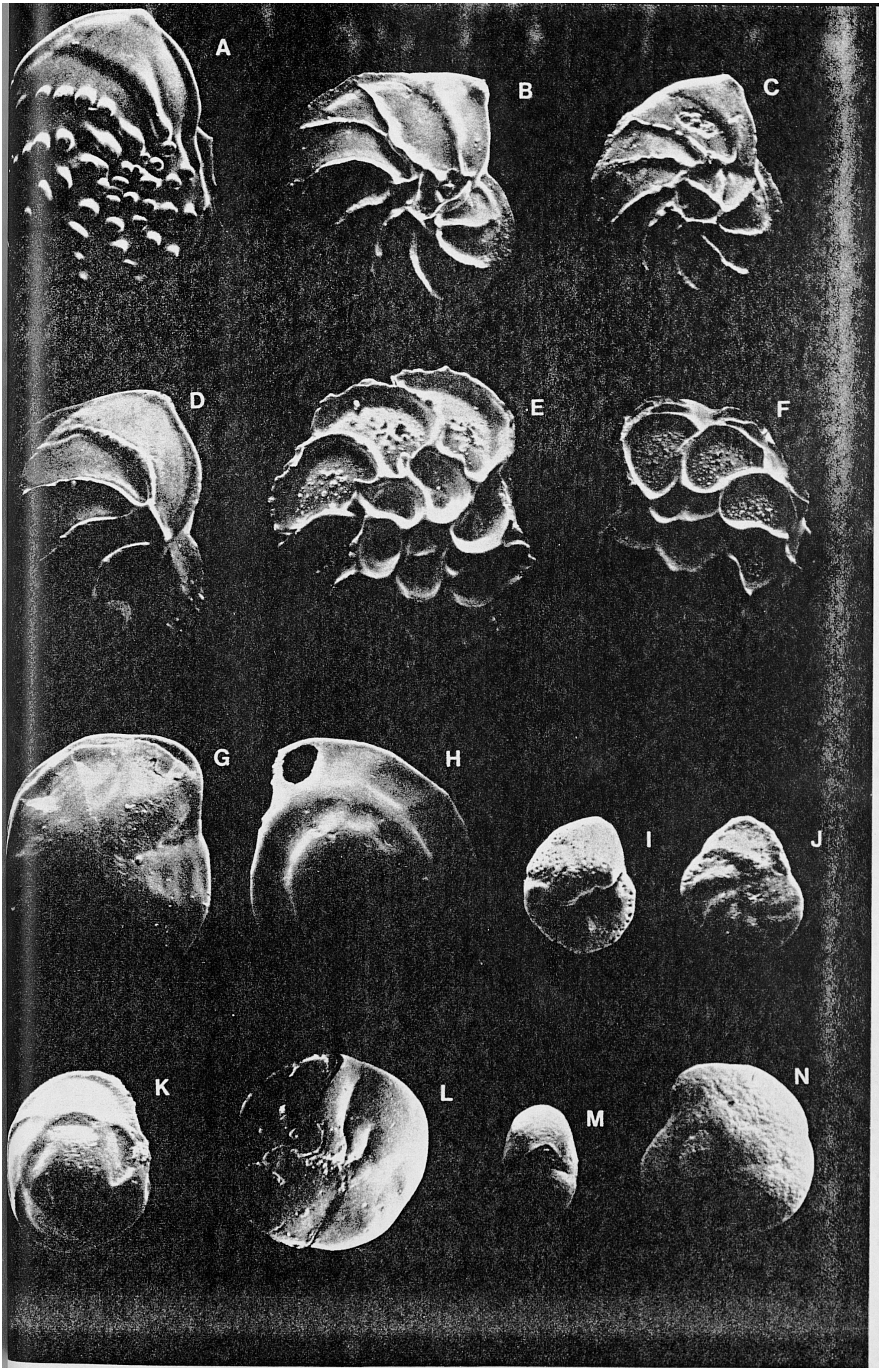
O. _Conorboides_ sp. MPK 5054 (ex CSB 4630) from 34.92-35.00m. x300.

P. _Conorboides_ sp. MPK 5055 (ex CSB 4619) from 30.62-30.69m. x470.

Q. _Verneuilinoides neocomiensis_ (Mjatliuk 1939) MPK 5056 (ex CSB 4706) from 69.28-69.36m. x111.

R. _Marsonella kummi_ Zedler 1961 MPK 5057 (ex CSB 4662) from 48.48-48.55m. x100.

S. _Haplophragmoides_ cf. _concavus_ (Chapman 1892) MPK 5058 (ex CSB 4774) from 84.58-84.68m. x60.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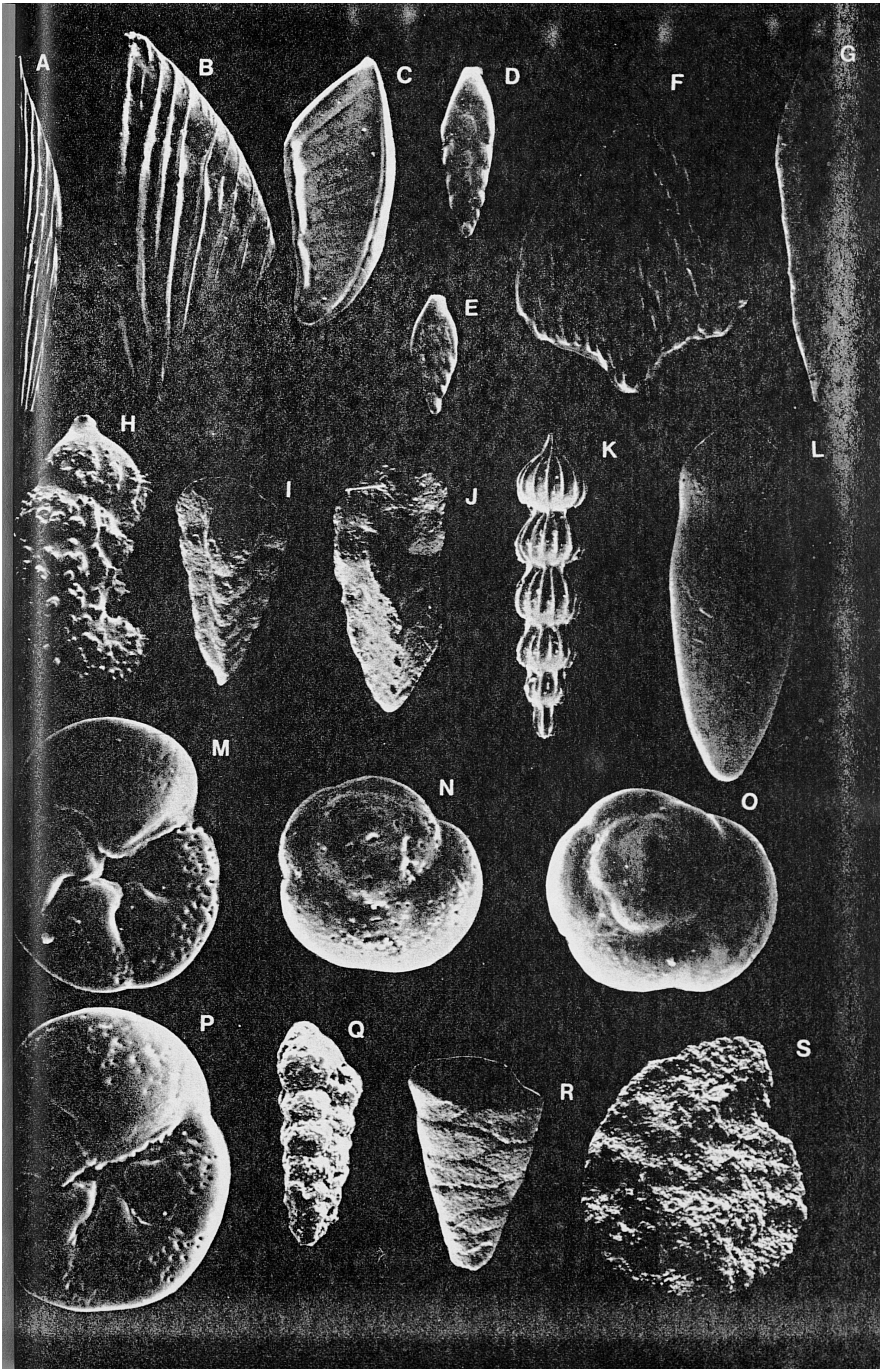
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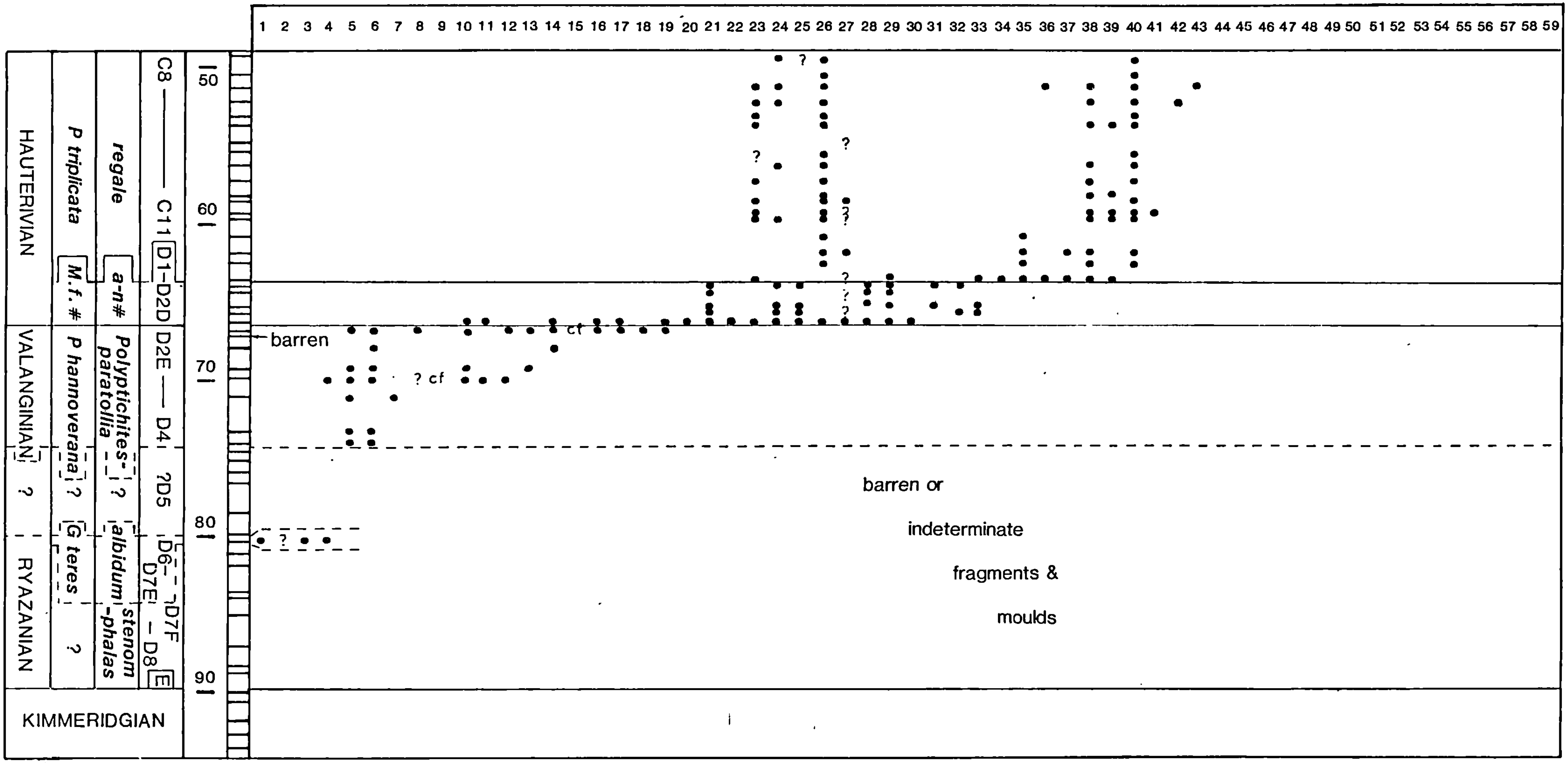


#M.f. Mandocythere frankei
#a-n amblygonium -noricum

Fig. 5.

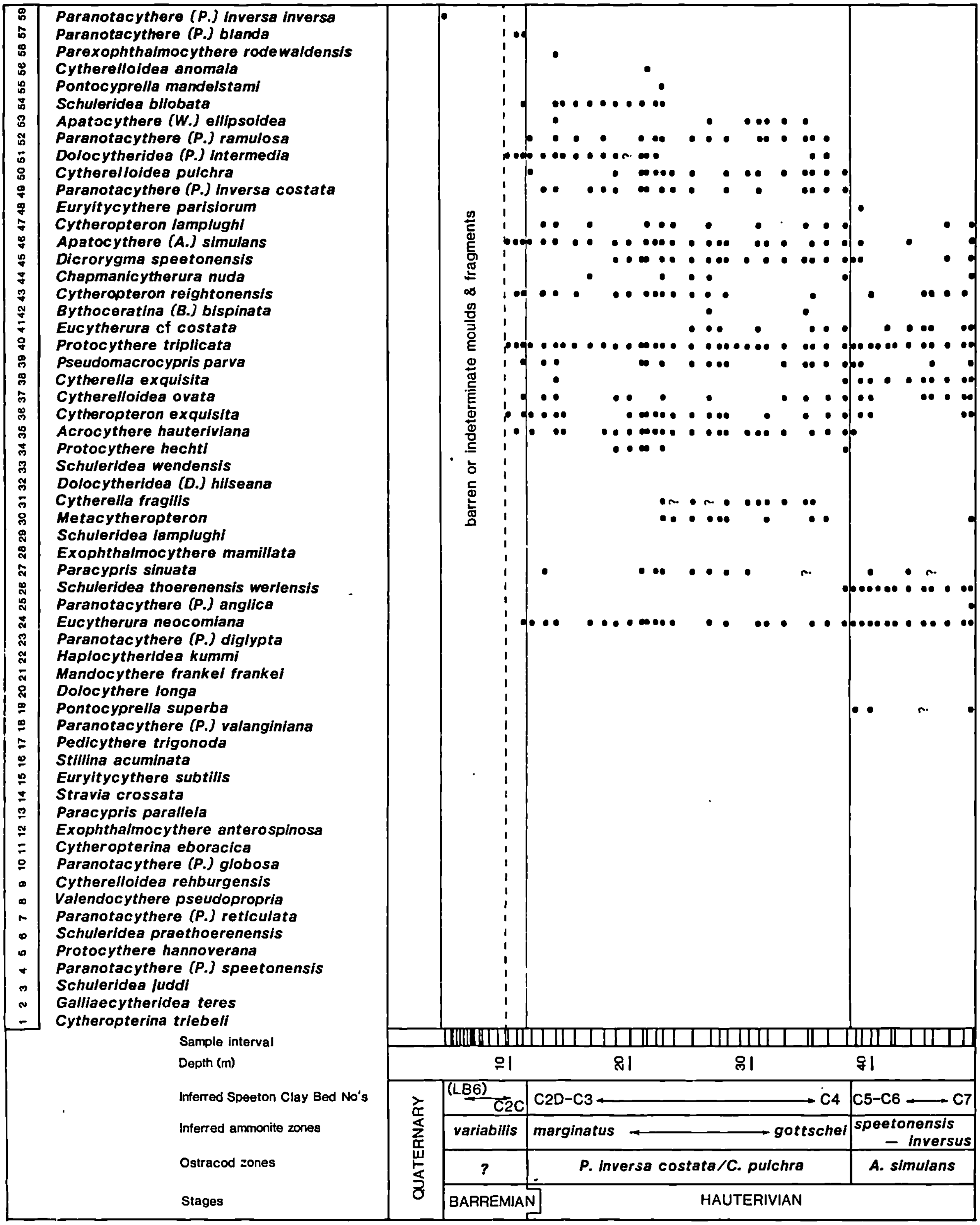

59 Paranotacythere (P.) inversa inversa
57 Paranotacythere (P.) blanda
58 Parexophthalmocythere rodewaldensis
56 Cytherelloidea anomala
55 Pontocyprella mandelstami
54 Schuleridea bilobata
53 Apatocythere (W.) ellipsoidea
52 Paranotacythere (P.) ramulosa
51 Dolocytheridea (P.) intermedia
50 Cytherelloidea pulchra
49 Paranotacythere (P.) inversa costata
48 Euryitycythere parisiorum
47 Cytheropteron lamplughi
46 Apatocythere (A.) simulans
45 Dicrorygma speetonensis
44 Chapmanicytherura nuda
43 Cytheropteron reightonensis
42 Bythoceratina (B.) bispinata
41 Eucytherura cf costata
40 Protocythere triplicata
39 Pseudomacrocypris parva
38 Cytherella exquisita
37 Cytherelloidea ovata
36 Cytheropteron exquisita
35 Acrocythere hauteriviana
34 Protocythere hechti
33 Schuleridea wendensis
32 Dolocytheridea (D.) hilseana
31 Cytherella fragilis
30 Metacytheropteron
29 Schuleridea lamplughi
28 Exophthalmocythere mamillata
27 Paracypris sinuata
26 Schuleridea thoerenensis werlensis
25 Paranotacythere (P.) anglica
24 Eucytherura neocomiana
23 Paranotacythere (P.) diglypta
22 Haplocytheridea kummi
21 Mandocythere frankei frankei
20 Dolocythere longa
19 Pontocyprella superba
18 Paranotacythere (P.) valanginiana
17 Pedicythere trigonoda
16 Stillina acuminata
15 Euryitycythere subtilis
14 Stravia crossata
13 Paracypris parallela
12 Exophthalmocythere anterospinosa
11 Cytheropterina eboracica
10 Paranotacythere (P.) globosa
9 Cytherelloidea rehburgensis
8 Valendocythere pseudopropria
7 Paranotacythere (P.) reticulata
6 Schuleridea praethoerenensis
5 Protocythere hannoverana
4 Paranotacythere (P.) speetonensis
3 Schuleridea juddi
2 Galliaecytheridea teres
1 Cytheropterina triebeli
barren or indeterminate moulds & fragments
Sample interval
Depth (m)
10
20
30
40
Inferred Speeton Clay Bed No's
(LB6)
C2C
C2D–C3
C4
C5–C6
C7
Inferred ammonite zones
variabilis
marginatus
gottschei
speetonensis — inversus
Ostracod zones
?
P. inversa costata/C. pulchra
A. simulans
Stages
QUATERNARY
BARREMIAN
HAUTERIVIAN

Fig. 6 Valanginian-Barremian Ostracoda from the Speeton Clay Formation off north-eastern England. Magnification x 75 unless otherwise stated. All material is deposited in the collections of the British Geological Survey, Keyworth, Nottingham, England. / palaeontological

A. *Protocythere hannoverana* Bartenstein & Brand, 1959.
MPK 5009 (ex CSB 4710/C2) from 73.20-73.30m.

B. *Schuleridea praethoerenensis* Bartenstein & Brand, 1959.
MPK 5010 (ex CSB 4703/C2) from 67.88-67.96m.

C. *Valendocythere pseudopropria* (Bartenstein & Brand, 1959).
MPK 5011 (ex CSB 4701/C8) from 66.84-66.92m.

D. *Cytherelloidea* cf *rehburgensis* Bartenstein & Brand, 1959.
MPK 5012 (ex CSB 4707/C3) from 69.79-69.84m.

E. *Euryitycythere* cf *subtilis* Bartenstein & Brand, 1959.
MPK 5013 (ex CSB 4701/C7) from 66.84-66.92m.

F. *Mandocythere frankei* (Triebel, 1938).
MPK 5014 (ex CSB 4700/C4) from 66.24-66.32m.

G. *Haplocytheridea kummi* (Triebel, 1938).
MPK 5015 (ex CSB 4700/C3) from 66.24-66.32m.

H. *Schuleridea lamplughi* Neale, 1962.
MPK 5016 (ex CSB 4696/C2) from 64.28-64.36m.

I. *Protocythere hechti* Triebel, 1938.
MPK 5017 (ex CSB 4694/C2) from 63.54-63.66m.

J. *Paranotacythere (Paranotacythere) diglypta* (Triebel, 1941)
MPK 5018 (ex CSB 4694/C5) from 63.54-63.66m. x 100

K. *Paranotacythere (Paranotacythere) inversa costata* (Kaye, 1963).
MPK 5019 (ex CSB 4577/C2) from 16.77-16.81m. x 100.

L. *Cytherelloidea pulchra* Neale, 1960.
MPK 5020 (ex CSB 4624/C2) from 32.76-32.84m.

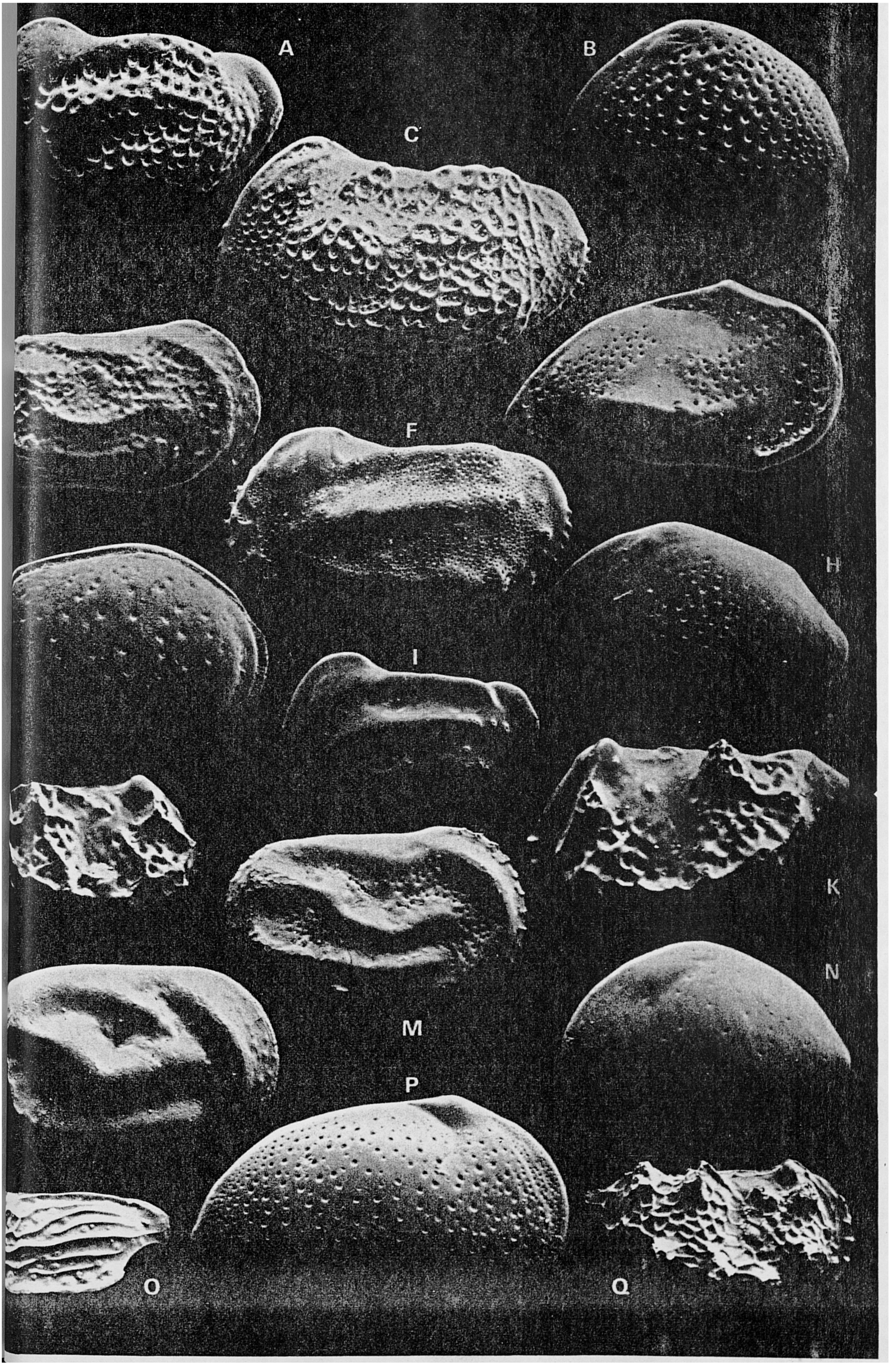
M. *Cytherelloidea ovata* Weber 1935.
MPK 5021 (ex CSB 4658/C2) from 46.49-46.57m.

N. *Apatocythere (Apatocythere) simulans* Triebel, 1940.
MPK 5022 (ex CSB 4612/C3) from 28.06-28.10m.

O. *Metacytheropteron* sp.
MPK 5023 (ex CSB 4633/C2) from 36.23-36.32m.

P. *Schuleridea bilobata* Triebel, 1938.
MPK 5024 (ex 4594/C2) from 22.22-22.26m.

Q. *Paranotacythere (Paranotacythere) ramulosa* (Sharpova, 1939).
MPK 5025 (ex CSB 4619/C2) from 30.62-30.69m.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Upper Jurassic stratigraphy of four shallow cored boreholes in the northern part of the Southern North Sea Basin (Blocks 42 and 47)

B. M. COX, G. K. LOTT, J. E. THOMAS and

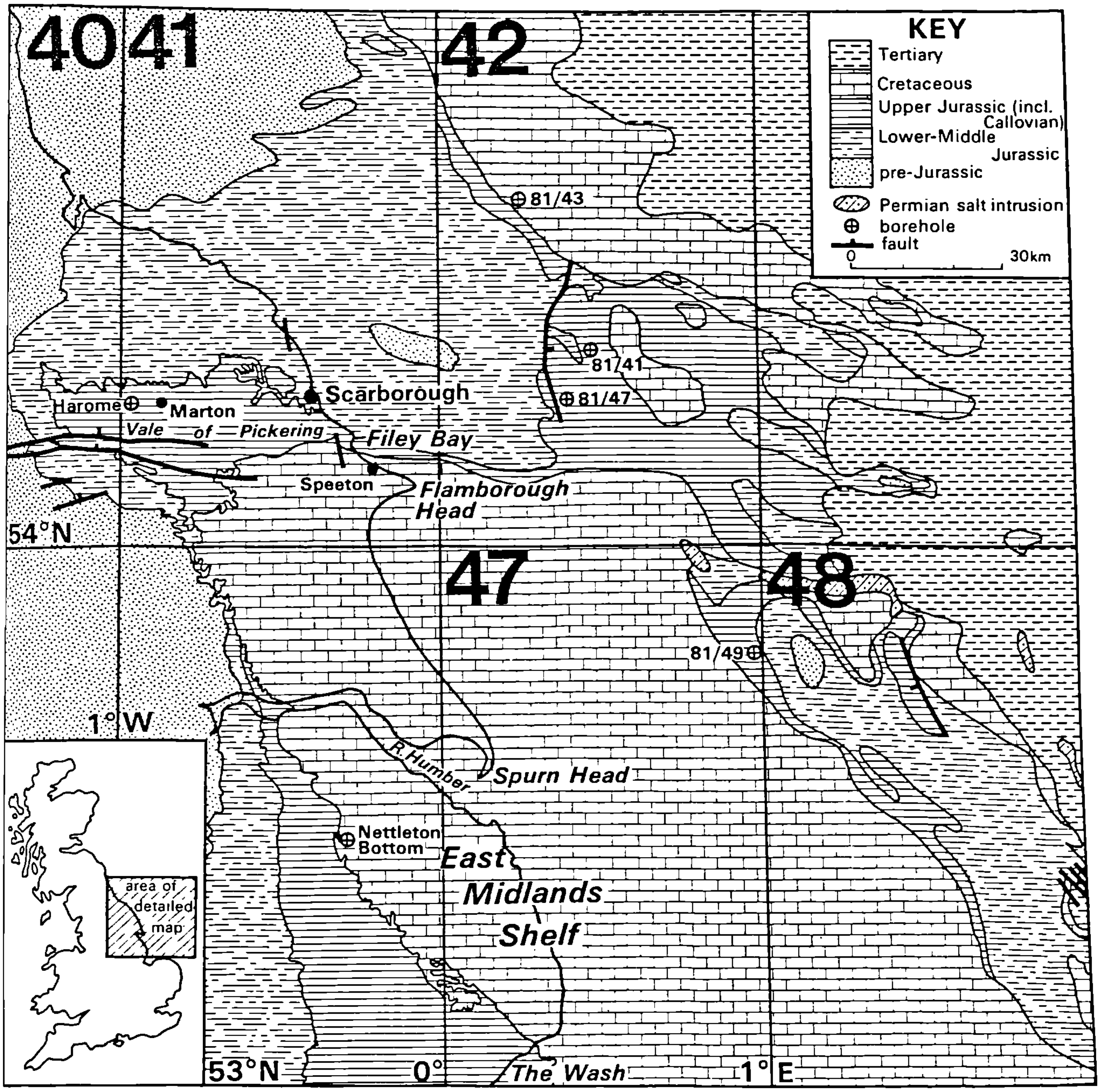
I. P. WILKINSON

SUMMARY: Four shallow cored boreholes (81/41, 81/43, 81/47 and 81/49) in the Southern North Sea Basin proved Late Jurassic mudstone sequences which compare closely in lithological and macrofaunal detail with the well known Kimmeridge Clay succession of southern and eastern England. Although together not giving complete stratigraphic coverage, all the Kimmeridgian zones from Baylei to Hudlestoni are represented; in Borehole 81/43, the latter zone is unconformably overlain by Lower Cretaceous strata. Thicknesses in boreholes 81/41 and 81/43 are comparable with those proved on the onshore East Midlands Shelf, but those in 81/47 and 81/49 appear to be two or three times thicker; these relationships fit the known disposition of the Sole Pit Basin. Borehole 81/41 also cored 21.1m of Middle-Upper Oxfordian strata. The ostracod faunas and dinoflagellate floras are discussed and range charts of selected taxa presented. The foraminifera are also considered.

In 1981, a series of shallow cored boreholes was drilled in the Southern North Sea by the Marine Geology Research Group of the British Geological Survey in order to identify the sub-Drift formations recorded in shallow reflection seismic profiles. Four boreholes (numbered 81/41, 81/43, 81/47 and 81/49) penetrated and cored the Kimmeridge Clay Formation. They are sited in North Sea Blocks 42 and 47 on the 1:250000 California and Spurn sheets (Fig. 1). Borehole 81/41 also cored the upper part of the underlying Corallian Formation (Corallian Group of onshore usage).

Although core recovery was imperfect, the cores show that the lithological and macrofaunal sequences are closely similar to those known from onshore sections in southern and central England where the Kimmeridge Clay consists of rhythmic sequences of silty mudstone, bituminous mudstone and oil shale, medium and dark grey fissile mudstone, and pale grey, calcareous mudstone with cementstone. Throughout the English outcrop, the lithological and macrofaunal sequences are remarkably constant, and it has been possible to define a standard sequence of 49 beds based on a combination of lithological and faunal characters (Gallois & Cox 1976; Cox & Gallois 1979, 1981). For all practical purposes, each bed boundary is isochronous. The relationship of the beds to the standard ammonite-based zones (= chronozones) and stages is shown in Fig. 2.

The standard sequence of beds has also provided a yardstick for the correlation of Kimmeridge Clay total gamma-ray logs which measure the rocks' natural radioactivity (Gallois 1973). Detailed correlations for the Kimmeridge Clay of the East Midlands (or Eastern England) Shelf have been achieved on this basis (Penn, Cox & Gallois 1980). The similarity of the



40
41
42
47
48
KEY
Tertiary
Cretaceous
Upper Jurassic (incl. Callovian)
Lower-Middle Jurassic
pre-Jurassic
Permian salt intrusion
borehole
fault
0
30km
81/43
81/41
81/47
81/49
Harome
Marton
Scarborough
Vale of Pickering
Filey Bay
Speeton
Flamborough Head
54°N
1°W
R. Humber
Spurn Head
Nettleton Bottom
East Midlands Shelf
53°N
0°
The Wash
1°E
area of detailed map

ALTERNATIVE STAGE NOMENCLATURES				ZONE	KIMMERIDGE CLAY STANDARD BED NOS	BOREHOLE
VOLGIAN (pars)	MIDDLE (pars)	PORTLANDIAN (pars)		*Glaucolithus*		not to scale
VOLGIAN (pars)	MIDDLE (pars)	PORTLANDIAN (pars)		*Albani*		
VOLGIAN (pars)	MIDDLE (pars)	KIMMERIDGIAN	UPPER	*Fittoni*		
VOLGIAN (pars)	MIDDLE (pars)	KIMMERIDGIAN	UPPER	*Rotunda*		
VOLGIAN (pars)	MIDDLE (pars)	KIMMERIDGIAN	UPPER	*Pallasioides*		
VOLGIAN (pars)	LOWER	KIMMERIDGIAN	UPPER	*Pectinatus*	46-49	
VOLGIAN (pars)	LOWER	KIMMERIDGIAN	UPPER	*Hudlestoni*	42 (pars) -45	81/43 (90 00m, 93 60m, 94 10m)
VOLGIAN (pars)	LOWER	KIMMERIDGIAN	UPPER	*Wheatleyensis*	40-42 (pars)	
VOLGIAN (pars)	LOWER	KIMMERIDGIAN	UPPER	*Scitulus*	37-39	81/47 (4 50m, 11 02m)
VOLGIAN (pars)	LOWER	KIMMERIDGIAN	UPPER	*Elegans*	36	81/47 (c17 5m)
KIMMERIDGIAN		KIMMERIDGIAN	LOWER	*Autissiodorensis*	33-35	81/47 (32 30m)
KIMMERIDGIAN		KIMMERIDGIAN	LOWER	*Eudoxus*	24-32	81/49 (11 30m, 24 00m)
KIMMERIDGIAN		KIMMERIDGIAN	LOWER	*Mutabilis*	15-23	81/41 (14 00m, F c41 0m)
KIMMERIDGIAN		KIMMERIDGIAN	LOWER	*Cymodoce*	5-14	F
KIMMERIDGIAN		KIMMERIDGIAN	LOWER	*Baylei*	1-4	F 45 00m, F, c46 0m
OXFORDIAN	UPPER			*Rosenkrantzi*		81/41
OXFORDIAN	UPPER			*Regulare*		81/41
OXFORDIAN	UPPER			*Serratum*		81/41
OXFORDIAN	UPPER			*Glosense*		81/41 (62 80m)
OXFORDIAN	MIDDLE			*Tenuiserratum*		81/41
OXFORDIAN	MIDDLE			*Densiplicatum*		81/41 (67 10m)

lithological sequences in the boreholes described below to those of the onshore area suggests that detailed correlations using gamma-ray logs should be feasible in the offshore area. The gamma-ray log for Borehole 81/41, the only borehole of the present suite for which one is available, is shown in Fig. 3.

Biostratigraphic control in the North Sea area is almost exclusively based on microfossils. Details of the ostracod, or in their absence the foraminifera, faunas and the dinoflagellate floras are discussed respectively in this paper by Wilkinson and Thomas. Certain Kimmeridgian macrofossils from the four boreholes are shown in Fig. 4.

Specimen and sample numbers (prefixed CSB), cited in the paper, refer to material in the collections of the British Geological Survey, Keyworth, Nottingham.

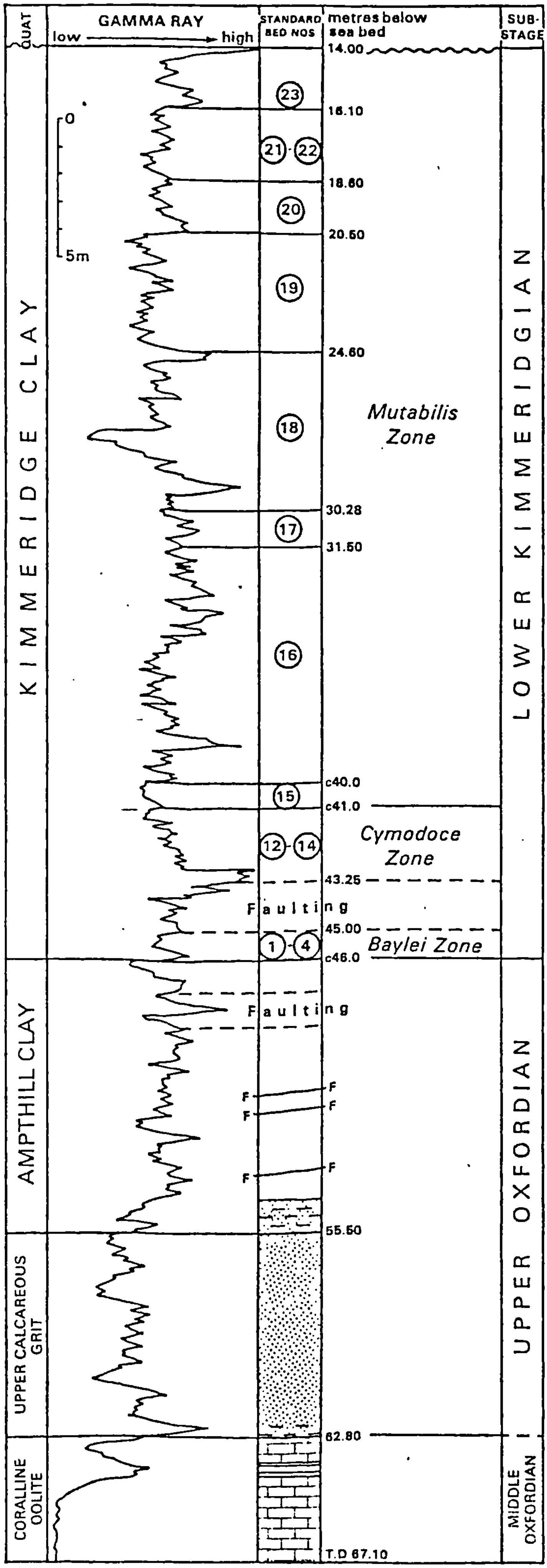
1. STRATIGRAPHIC DETAILS

There is no stratigraphic overlap between the sequences proved in the four boreholes (Fig. 2). In the following details, they are discussed in stratigraphic order from oldest (81/41) to youngest (81/43). Throughout the paper, the term Kimmeridgian is used in its fullest sense i.e. Baylei Zone to Fittoni Zone inclusive.

1.1 Borehole 81/41 (BGS registered no. 54/00/593)

Lat. 54° 22.197'N Long. 0° 27.284'E

Borehole 81/41 cored 53.1m of Upper Jurassic strata below Quaternary deposits at a depth of 14.0m (Fig. 3). Core recovery was poor in the


QUAT
GAMMA RAY
low → high
STANDARD BED NOS
metres below sea bed
SUB-STAGE
14.00
16.10
18.60
20.60
24.60
30.28
31.50
c40.0
c41.0
43.25
45.00
c46.0
55.50
62.80
T.D 67.10
0
5m
23
21 - 22
20
19
18
17
16
15
12 - 14
1 - 4
Faulting
Faulting
F
Mutabilis Zone
Cymodoce Zone
Baylei Zone
KIMMERIDGE CLAY
AMPTHILL CLAY
UPPER CALCAREOUS GRIT
CORALLINE OOLITE
LOWER KIMMERIDGIAN
UPPER OXFORDIAN
MIDDLE OXFORDIAN

highest two metres and the youngest strata collected (at 16.90m) belong to the Mutabilis Zone; they are rich in small '*Astarte*' which characterize Beds 21-22 of the standard Kimmeridge Clay sequence (Bed 22 is the Supracorallina Bed, which takes its name from a species of this bivalve). The Mutabilis Zone is at least 26m thick and is probably completely cored (Figs 2 and 3). Bed 20 (fissile mudstone with plasters of *Aulacostephanus eulepidus* (Schneid)), Bed 18 (medium and pale grey calcareous mudstone with a cementstone band) and Bed 16 (interbedded medium grey, sparsely shelly mudstone and fissile, brownish grey mudstone with quasi-oil shale) are readily identifiable.

Compared with onshore sequences, the underlying Cymodoce and Baylei zones appear thin. The cores at this stratigraphic level are disturbed and contain sheared surfaces and 'beef'-filled joints which suggest that faulting, probably between c 43.3m and 45.0m, may have cut out a thickness of strata. Specimens of *Rasenia*, indicating the Cymodoce Zone, occur from 42.35m to 43.09m. The base of the Kimmeridgian is taken at c 46.0m where very pale grey burrow-mottled mudstone with phosphatized bivalves rests on pale to medium grey, silty mudstone with *Oxytoma*.

The underlying Upper Oxfordian mudstones are probably also reduced in thickness as a result of a series of minor faults, for instance at 47.15m - 48.32m, 50.65m - 50.70m, 51.24m - 51.35m and 53.40m - 53.60m. Only c 8.5m were proved compared with a thickness of c 50m at the western end of the Vale of Pickering, North Yorkshire (Cox & Richardson 1982). The mudstones are medium and pale grey in colour and show signs of phosphatization. Their macrofauna is dominated by bivalves including *Deltoideum delta* (Wm Smith), *Oxytoma*, *Protocardia*, pectinids and *Thracia*; belemnites and ammonites (*Ringsteadia*?) are also recorded. The basal metre consists of bioturbated glauconitic sandy mudstone with *Cylindroteuthis*, serpulids and wood fragments; it compares with the basal bed of the Ampthill Clay recorded in the Vale of Pickering by Wright (1972, p.2?7; 1980, p.75).

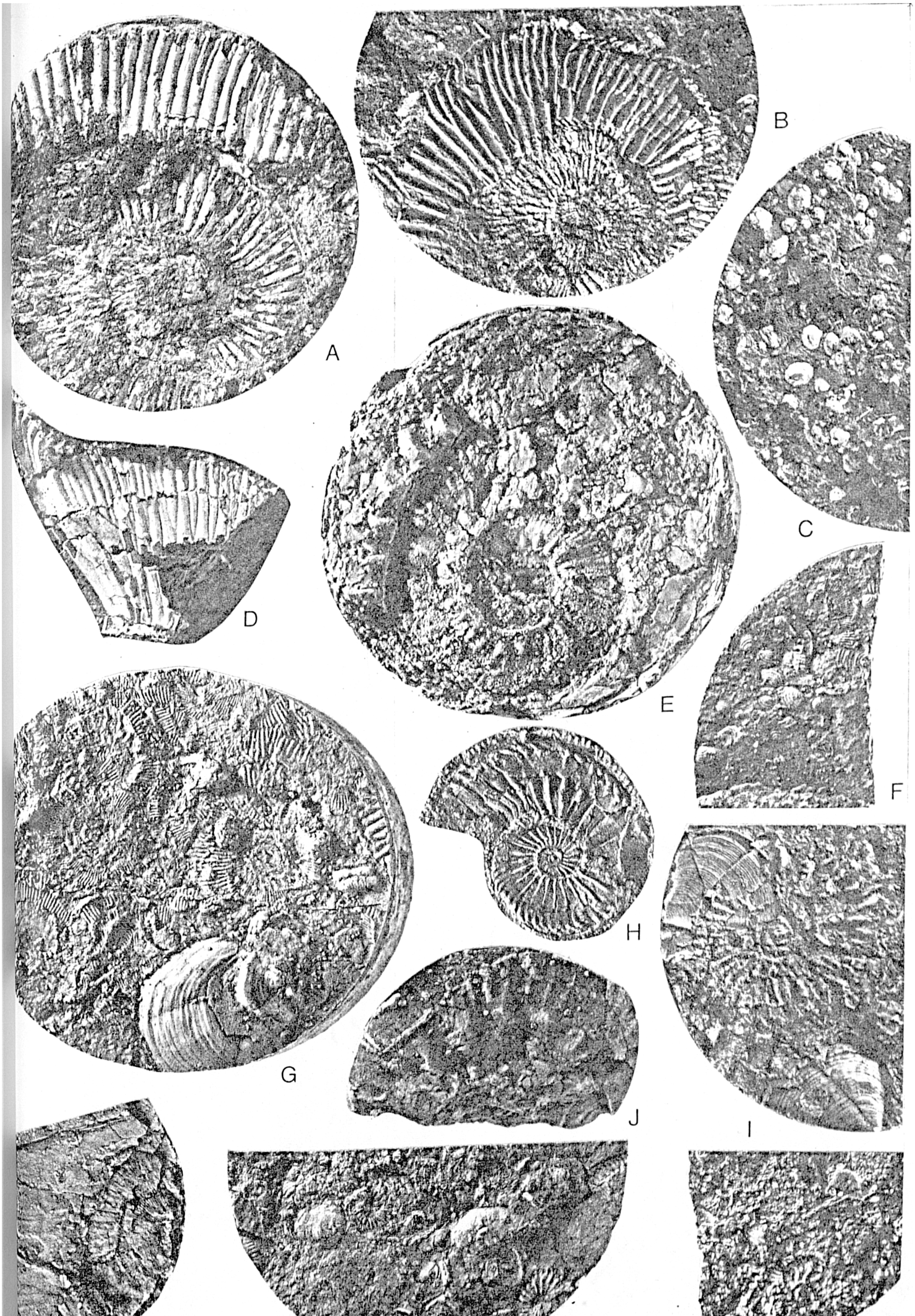
The sequence ends with c 11.6m of Oxfordian limestones and sandstones with thin mudstones which belong to the Corallian Group (Upper Calcareous Grit and Coralline Oolite formations).

Borehole 81/49 (BGS registered no. 53/00/1231)

Lat. 53° 48.149'N   Long. 0° 58.591'E

Borehole 81/49 cored 12·7m of Kimmeridge Clay below Quaternary deposits at a depth of 11.30m. The cores, severely disturbed by drilling, consist of medium grey, fissile, shelly mudstone; very fissile, brownish-grey, moderately shelly and shelly mudstone; oil shale; and thin interbeds of pale and very pale grey, calcareous mudstone. The macrofauna includes the ammonites Amoeboceras (Amoebites) (Fig 4H) and A. (Nannocardioceras) (Fig 4L), Aspidoceras (Fig 4L) (and Laevaptychus) (Fig 4I), Aulacostephanus and Sutneria (Fig 4M); the bivalves Bositra, Corbulomima, Grammatodon, 'Inoceramus', Liostrea, 'Lucina' minuscula Blake, nuculoids (including Dacryomya), Oxytoma and Protocardia; the gastropods Dicroloma and 'Procerithium'; together with serpulids, fish fragments, Lingula and brassy pyritized specimens of the microcrinoid Saccocoma.

This assemblage indicates the Eudoxus Zone and, taken with the lithologies, indicates Bed 29 of the standard Kimmeridge Clay sequence. Of particular interest is the occurrence of Saccocoma at 13.35m, 13.40m and 13.56m (CSB 6109, 6110, 6112, 6123). This fossil provides two widespread marker bands in the Eudoxus Zone of eastern England (Gallois and Cox 1976, p. 21), and it is probably the younger one of these which is recorded in Borehole 81/49.


A
B
C
D
E
F
G
H
I
J
K
L
M

3. Borehole 81/47 (BGS registered no. 54/+00/598)

[Lat. 54° 16.586'N   Long. 0° 23.168'E

Borehole 81/47 cored 27.8m of Kimmeridge Clay below Quaternary deposits at a depth of 4.5m. Although core recovery was reasonably good, some core runs were considerably damaged by drilling and thicknesses distorted. Therefore, specific depths within any single core run are uncertain. The general disturbed nature of the core makes recognition of any minor faulting impossible.

The sequence consists of medium and dark grey mudstones interbedded with fissile, brownish-grey, bituminous mudstone and oil shale; small amounts of pale or very pale grey calcareous mudstone are present. The Lower-Upper Kimmeridgian boundary, at the junction of the Autissiodorensis and Elegans zones, is at c 17.5m. The highest Aulacostephanus was recorded at c 18.0m and the lowest Pectinatites at c 17.4m. A brownish-grey cementstone at 10.90 - 11.02m may be a correlative of that which marks the base of the Scitulus Zone from Dorset (the Yellow Ledge Stone Band) to the Humber. The sequence proved in Borehole 81/47 includes representatives of Beds 34 to 37 inclusive.

4. Borehole 81/43 (BGS registered no. 54/+00/595)

[Lat. 54° 38.919'N   Long. 0° 14.509'E

Borehole 81/43 cored 4.23m of Kimmeridge Clay below the Coprolite Bed at the base of the Speeton Clay (Cretaceous) at a depth of 89.87m. The Kimmeridge Clay consists of c3.0m of interbedded oil shale, bituminous mudstone and medium to dark grey mudstones, overlain by c 1.2m of pale grey, highly calcareous mudstone.

The oil shales and bituminous mudstones are shelly and very shelly, and contain a typical macrofauna of common 'Lucina' minuscula Blake (Fig 4C), rare small oysters, Dentalium and fish scales, together with shell fragments, debris and spat; foraminifera-spotting is also present. Pectinatites occurs throughout and indicates a Late Kimmeridgian age. Most of the specimens are fragments and are unidentifiable at species level, but the assemblage includes P. (Virgatosphinctoides) cf. donovani Cope at 93.17 – 93.20m (CSB 4813-4) (Fig 4B) and P. (V.) cf. reisiformis Cope at 93.51m (CSB 4820) (Fig 4A). A number of other fragments probably belong to the latter species which has been used as a subzonal index for the older part of the Hudlestoni Zone (Cope 1974a). The lithologies and fauna indicate the presence of Beds 42-44 of the standard Kimmeridge Clay sequence. Ostracod faunas suggest that the Wheatleyensis-Hudlestoni zonal boundary lies between 92.80m and 93.70m (Wilkinson, this paper), and in conjunction with the evidence of the ammonites cited above, the boundary is taken at 93.60m.

Near Speeton on the North Yorkshire coast, the Coprolite Bed apparently rests on Kimmeridge Clay of the older part of the Pectinatus Zone (Cope 1980, p.83). Cope (1974b, pp. 213-214) recorded a single specimen of Pectinatites (P.) proboscide (Buckman) from immediately beneath the Speeton Clay.

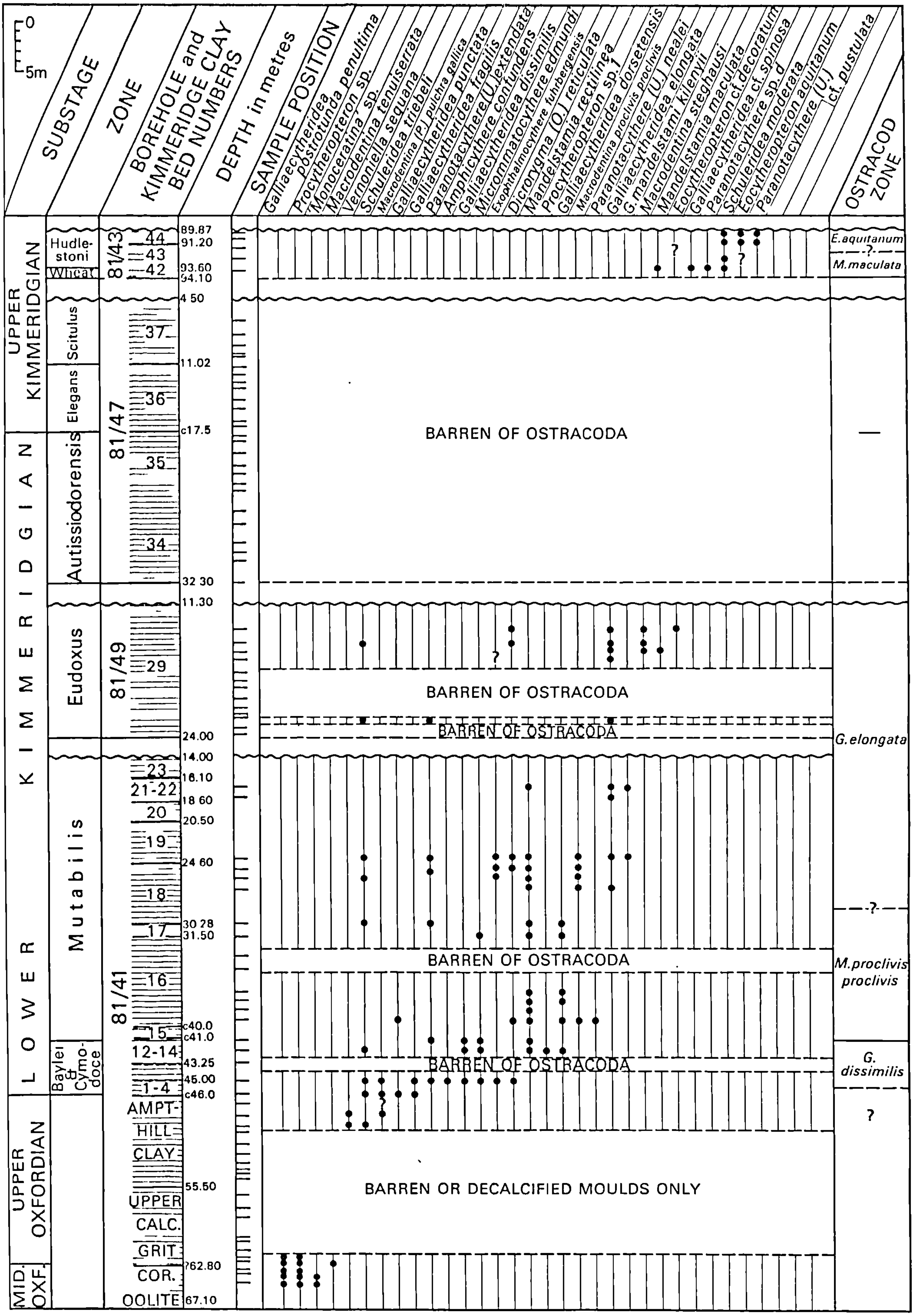
Details of the Cretaceous (Ryazanian-Barremian) sequence in Borehole 81/43 are described by Lott, Fletcher and Wilkinson (1986).

2. CALCAREOUS MICROPALAEONTOLOGY

Kimmeridgian ostracod sequences are now well known following detailed study of standard bed-numbered Kimmeridge Clay core samples from eastern England (Wilkinson 1983a, b) and earlier work on the type Kimmeridgian sequences of Dorset (Kilenyi 1969; Christensen & Kilenyi 1970). Amongst Kimmeridgian microfossils, ostracods are proving to be reliable and precise biostratigraphic indicators and in this respect, as far as published data is concerned, are superior to foraminifera on which little has been published since Lloyd's work (1959; 1962). For the four boreholes described in the present paper, the foraminifera have been studied in detail only at those Kimmeridgian horizons where ostracods are absent. The distribution of selected ostracod taxa is shown in Fig. 5 .

Oxfordian strata were drilled only in Borehole 81/41, and their ostracod fauna is extremely sparse. The Middle Oxfordian subspecies _Galliaecytheridea postrotunda penultima_ Whatley MS dominates the Coralline Oolite assemblages, and _Vernoniella sequana_ Oertli was recovered from 48.25–49.50m (CSB 7162-3) in the Upper Oxfordian Ampthill Clay. _Macrodentina pulchra gallica_ Glashoff, a useful marker for the Late Oxfordian and basal Kimmeridgian, was found from 44.93 –48.35m (CSB 7159-62), and at 46.4 – 46.5m (CSB 7160), _Galliaecytheridea punctata_ Kilenyi occurs in flood proportions.

The ostracod faunas in Borehole 81/41 indicate that the Kimmeridgian-Oxfordian boundary is between 45.0m and 46.5m. The sample at 44.93 –45.00m (CSB 7159) contains flood proportions of _Schuleridea triebeli_ (Steghaus), together with _Macrodentina pulchra gallica_, _Galliaecytheridea fragilis_ Kilenyi, _G. dissimilis_ Oertli, _Micrommatocythere edmundi_ Wilkinson, _Exophthalmocythere fuhrbergensis_ Steghaus, _Dicrorygma reticulata_



0
5m
SUBSTAGE
ZONE
BOREHOLE and KIMMERIDGE CLAY BED NUMBERS
DEPTH in metres
SAMPLE POSITION
Galliaecytheridea postrotunda
Procytheropteron penultima
Monoceratina sp.
Macrodentina tenuiserrata
Vernoniella sequana
Schuleridea triebeli
Macrodentina (P.) pulchra gallica
Galliaecytheridea punctata
Paranotacythere (U.) extendata
Amphicythere confundens
Galliaecytheridea fragilis
Micrommatocythere edmundi
Exophthalmocythere fuhrbergensis
Dicrorygma (O.) reticulata
Mandelstamia rectilinea
Procytheropteron sp.1
Galliaecytheridea dorsetensis
Macrodentina proclivis proclivis
Paranotacythere (U.) nealei
Galliaecytheridea elongata
G. mandelstami kilenyii
Macrodentina steghausi
Mandelstamia maculata
Eocytheropteron cf. decoratum
Galliaecytheridea cf. spinosa
Paranotacythere sp.d
Schuleridea moderata
Eocytheropteron aquitanum
Paranotacythere (U.) cf. pustulata
OSTRACOD ZONE
UPPER KIMMERIDGIAN
LOWER KIMMERIDGIAN
UPPER OXFORDIAN
MID. OXF.
Hudlestoni
Wheat.
Scitulus
Elegans
Autissiodorensis
Eudoxus
Mutabilis
Baylei & Cymodoce
81/43
81/47
81/49
81/41
44
43
42
37
36
35
34
29
23
21-22
20
19
18
17
16
15
12-14
1-4
AMPT-HILL-CLAY
UPPER CALC. GRIT
COR. OOLITE
89.87
91.20
93.60
94.10
4 50
11.02
c17.5
32 30
11.30
24.00
14.00
16.10
18 60
20.50
24 60
30 28
31.50
c40.0
c41.0
43.25
45.00
c46.0
55.50
?62.80
67.10
BARREN OF OSTRACODA
BARREN OF OSTRACODA
BARREN OF OSTRACODA
BARREN OF OSTRACODA
BARREN OF OSTRACODA
BARREN OR DECALCIFIED MOULDS ONLY
E. aquitanum
M. maculata
G. elongata
M. proclivis proclivis
G. dissimilis
?

Christensen, Paranotacythere extendata Bassiouni and Amphicytherura confundens Oertli. This assemblage compares closely with that from the basal Kimmeridgian Baylei Zone of the Wash area (Wilkinson 1983a) and falls within the Galliaecytheridea dissimilis (ostracod) Zone. The earliest occurrence of the foraminifer Vaginulina prima (d'Orbigny), which is a good marker for the basal Kimmeridgian, is at 43.40 -43.50m (CSB 7158).

The succeeding Kimmeridgian ostracod zonal assemblage, characterized by Macrodentina proclivis proclivis Malz, appears between 39.7m and 41.45m in Borehole 81/41; this zonal boundary correlates with the base of Bed 15 (base Mutabilis Zone) of the standard Kimmeridge Clay sequence. M. proclivis proclivis is accompanied by Paranotacythere (Unicosta) nealei Bassiouni; the latter taxon is not found in strata older than the Mutabilis Zone in East Anglia, but it appears as early as the Baylei Zone in Germany (Bassiouni 1974). The base of the overlying Galliaecytheridea elongata (ostracod) Zone occurs between 27.2m and 30.3m. Core loss in this interval prevents a more accurate determination of the zonal boundary which correlates with the base of Bed 18 onshore (Wilkinson 1983a). The highest sample examined in Borehole 81/41, at 16.90—17.00m (CSB 7142), contains fragments of Galliaecytheridea mandelstami kilenyii Wilkinson indicating that this horizon is still within the G. elongata (ostracod) Zone and no younger than Bed 23.

In Borehole 81/49, the zonal index species G. elongata Kilenyi appears first at 22.18—22.28m (CSB 6068), samples below this being barren. At 15.50—15.60m (CSB 6060), the presence of Macrodentina steghausi (Klinger) indicates the younger subzone of the G. elongata (ostracod) Zone (equivalent to Beds 24-31 of the standard Kimmeridge Clay sequence), but this taxon declines in numbers in the highest sample, at 13.50—13.60m (CSB 6058), where G. elongata occurs in flood proportions (nearly 80% of the total ostracod assemblage).

Ostracods were completely absent from samples taken in Borehole 81/47 (CSB 7910-35). In Britain, the late Eudoxus to early Scitulus zonal interval is proving to be persistently barren of ostracods. The foraminifer Pseudolamarckina polonica Bielecka & Pozaryski occurs between 10.3m and 29.00m; the appearance of this taxon seems to be a useful marker for the mid-Kimmeridgian. Citharina macilenta Terquem is recorded from 18.54m to 29.00m and, if the range given by Kuznetsova (1979) is reliable, this interval must be no younger than the Autissiodorensis Zone at which level that foraminifer is said to become extinct. The dominance of agglutinated foraminifera in several samples may be related to the low oxygen conditions which presumably existed at the time of oil shale formation. These conditions may also be responsible for the rarity and low diversity of the foraminiferal faunas above 13m in Borehole 81/47.

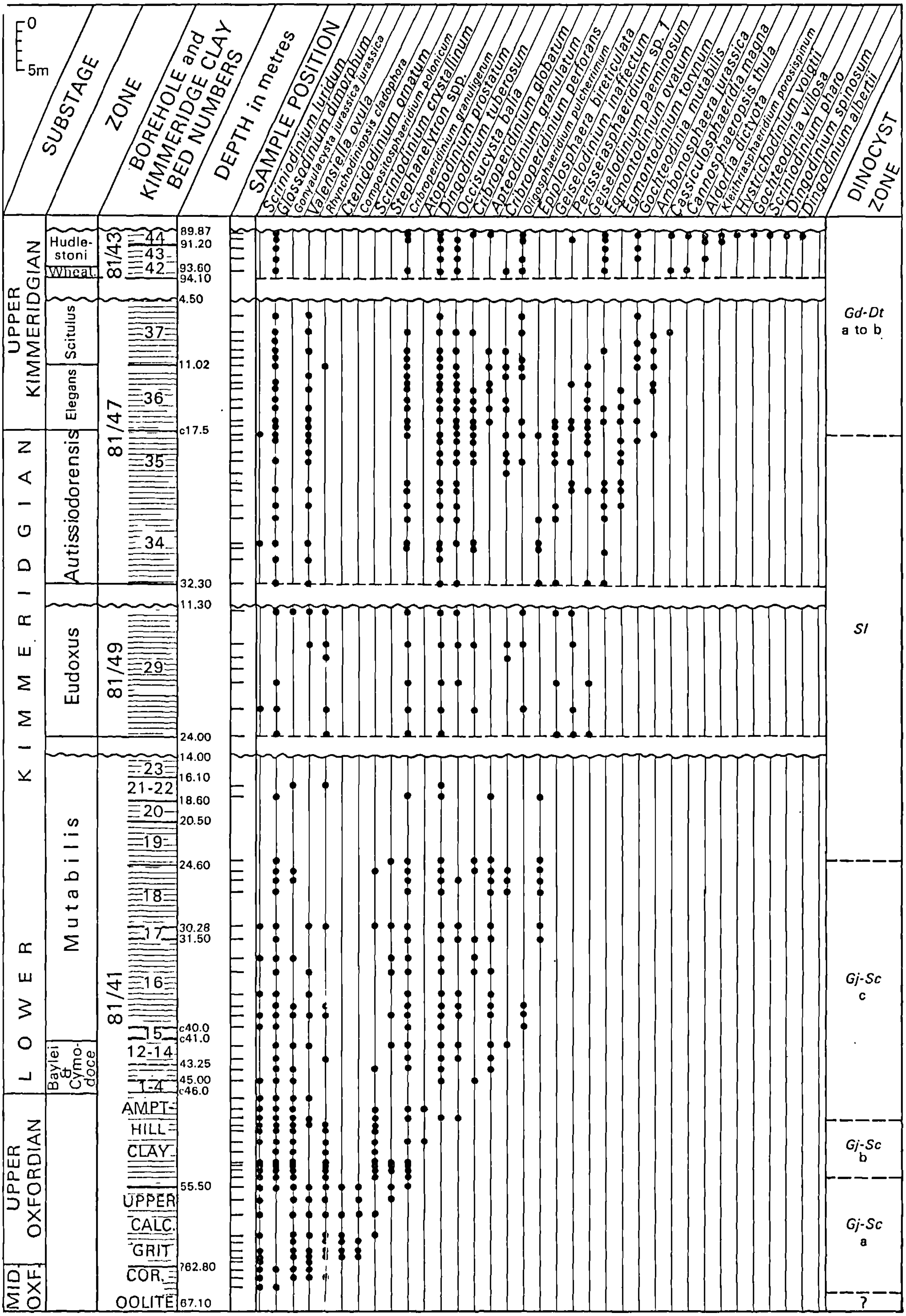
The youngest Kimmeridgian microfaunas were recovered from Borehole 81/43 where the lowest sample at 93.70 – 93.80m (CSB 4788) contained flood proportions of Mandelstamia (Xeromandelstamia) maculata Kilenyi. This species is an excellent marker for the younger part of the Wheatleyensis Zone in Britain, and is the zonal index for the equivalent ostracod zone (Wilkinson 1983a). The species Eocytheropteron aquitanum (Donze) together with Paranotacythere (Unicosta) cf. pustulata (Kilenyi) occurred in samples from 90.00m to 90.80m (CSB 4784-5). This combination of species is known in eastern England only from the lower part of Bed 44 of the Kimmeridge Clay (Hudlestoni Zone) (Wilkinson 1983a,b).

3. PALYNOLOGY

The palynology of Upper Jurassic sequences from northwest Europe has received considerable attention over the last thirty years, for example from Klement (1960), Gitmez & Sarjeant (1972) and Raynaud (1978). Many accounts concentrate on dinoflagellate cysts (dinocysts) as these have proved to be the most biostratigraphically useful palynomorph group in this part of the geological column. They have been used as the basis of various palynological zonations, most recently by Woollam & Riding (1983).

In the four boreholes described in the present paper, over 100 dinocyst taxa were identified of which many proved to be relatively long-ranging and thus of limited stratigraphic value. The distribution of 34 of the more important taxa is shown in Fig. 6, and the dinocyst assemblages are discussed below in sequential order from the oldest to the youngest.

A number of dinocysts including Glossodinium dimorphum Ioannides, Stavrinos & Downie, Scriniodinium luridum (Deflandre) Klement, Gonyaulacysta jurassica subsp. jurassica (Deflandre) Norris & Sarjeant emend. Sarjeant, Valensiella ovula (Deflandre) Eisenack, Hystrichogonyaulax cladophora (Deflandre) Stover & Evitt and Cribroperidinium granuligerum (Klement) Stover & Evitt range throughout much of the Oxfordian-Kimmeridgian sequence proved in Borehole 81/41, and Stephanelytron spp. occurs sporadically. G. dimorphum, which has a known range base in the Middle Oxfordian (Tenuiserratum Zone) occurs in the Coralline Oolite at 63.30-63.40m (CSB 7181). Other taxa of particular interest include Ctenidodinium ornatum (Eisenack) Deflandre and Compositosphaeridium polonicum (Gorka) Erkmen & Sarjeant which have recorded range tops in the Upper Calcareous Grit at 55.80-55.90m (CSB 7171); the



0
5m
SUBSTAGE
ZONE
BOREHOLE and KIMMERIDGE CLAY BED NUMBERS
DEPTH in metres
SAMPLE POSITION
Scriniodinium luridum
Glossodinium dimorphum
Gonyaulacysta jurassica jurassica
Valensiella ovula
Rhynchodiniopsis cladophora
Ctenidodinium ornatum
Compositosphaeridium polonicum
Scriniodinium crystallinum
Stephanelytron spp.
Cribroperidinium granuligerum
Atopodinium prostatum
Dingodinium tuberosum
Occisucysta balia
Apteodinium globatum
Cribroperidinium granulatum
Cribroperidinium perforans
Oligosphaeridium pulcherrimum
Epiplosphaera bireticulata
Geiselodinium inaffectum
Perisseiasphaeridium sp. 1
Geiselodinium paeminosum
Egmontodinium ovatum
Egmontodinium torynum
Gochteodinia mutabilis
Ambonosphaera jurassica
Cassiculosphaeridia magna
Cannosphaeropsis thula
Aldorfia dictyota
Kleithriasphaeridium porosispinum
Hystrichodinium voigtii
Gochteodinia villosa
Scriniodinium pharo
Dingodinium spinosum
Dingodinium albertii
DINOCYST ZONE
UPPER KIMMERIDGIAN
LOWER KIMMERIDGIAN
UPPER OXFORDIAN
MID. OXF.
Hudlestoni
Wheat.
Scitulus
Elegans
Autissiodorensis
Eudoxus
Mutabilis
Baylei & Cymodoce
81/43
81/47
81/49
81/41
44
43
42
37
36
35
34
29
23
21-22
20
19
18
17
16
15
12-14
1-4
AMPT-HILL CLAY
UPPER CALC. GRIT
COR. OOLITE
89.87
91.20
93.60
94.10
4.50
11.02
c17.5
32.30
11.30
24.00
14.00
16.10
18.60
20.50
24.60
30.28
31.50
c40.0
c41.0
43.25
45.00
c46.0
55.50
?62.80
67.10
Gd-Dt a to b
Sl
Gj-Sc c
Gj-Sc b
Gj-Sc a
?

extinction of the latter taxon is a marker for the top of Subzone a of the Gonyaulacysta jurassica-Scriniodinium crystallinum (dinocyst) Zone of Woollam & Riding (1983). Atopodinium prostatum Drugg, with a known range top in the Upper Oxfordian Serratum Zone, is recorded at 47.20-47.30m (CSB 7161) and 51.00-51.10m (CSB 7165). Although not previously known from strata older than Kimmeridgian, Occisucysta balia Gitmez and Dingodinium tuberosum (Gitmez) Fisher & Riley were both recorded at 48.25-48.35m (CSB 7162), about two metres below the Oxfordian-Kimmeridgian boundary which according to macrofossil and ostracod evidence is fixed at c.46m. Other characteristic Kimmeridgian taxa begin to appear above this level; these include Cribroperidinium globatum (Gitmez & Sarjeant) Helenes at 44.93-45.00m (CSB 7159), Apteodinium granulatum Eisenack at 43.40-43.50m (CSB 7158), Cribroperidinium perforans (Cookson & Eisenack) Below at 41.45-41.53m (CSB 7156), Oligosphaeridium pulcherrimum (Deflandre & Cookson) Davey & Williams sensu Gitmez & Sarjeant (1972) at 39.60-39.70m (CSB 7155) and Epiplosphaera bireticulata Klement at 31.50-31.60m (CSB 7149). Scriniodinium crystallinum (Deflandre) Klement is recorded in samples as high as 25.00-25.10m (CSB 7145) in the Mutabilis Zone.

Many of the taxa recorded in Borehole 81/41 also occur in Borehole 81/49. These include S. luridum, Gloss. dimorphum. V. ovula, H. cladophora, C. globatum, C. perforans, C. granuligerum, Occ. balia, D. tuberosum, Gony. jurassica subsp. jurassica and Olig. pulcherrimum. In addition, Geiselodinium inaffectum Drugg and G. paeminosum Drugg, reported from the Eudoxus and Autissiodorensis zones of England and Germany by Drugg (1978), are present at 24.00m (CSB 8413) and 18.98m (CSB 8411), and the latter species again at 11.30m (CSB 8407). Perissieasphaeridium sp. 1, an informally named morphotype of Davey (1982), also first appears in Borehole 81/49.

The next youngest assemblages occur in Borehole 81/47, but taxa recorded in boreholes 81/41 and 81/49 are still present. These include G. dimorphum, V. ovula, D. tuberosum, Occ. balia, Olig. pulcherrimum, A. granulatum and Cribroperidinium spp. Geiselodinium spp. continue to occur up to 11.10-11.20m (CSB 7925) and their known range is thereby extended into the Elegans Zone; at some levels they are particularly abundant, for example, at 15.30-15.40m (CSB 7930), 16.20-16.30m (CSB 7931), 16.90-17.00m (CSB 7932), 18.54-18.61m (CSB 7917) and 19.48-19.54m (CSB 7919). S. luridum has a range top at 17.80-17.87m (CSB 7913) in the Autissiodorensis Zone. Five additional species first appear in Borehole 81/47 - Egmontodinium ovatum (Gitmez & Sarjeant) Riley at 32.20-32.30m (CSB 7935), E. torynum (Cookson & Eisenack) Davey at 25.00-25.10 (CSB 7933), Gochteodinia mutabilis (Riley) Davey at 19.48-19.54m (CSB 7919), Ambonosphaera jurassica (Gitmez & Sarjeant) Fensome at 18.54-18.61m (CSB 7917) and Cassiculosphaeridia magna Davey at 8.00-8.10m (CSB 7921). This early occurrence of G. mutabilis in the Autissiodorensis Zone extends the previously recorded range of the species (Woollam & Riding pers. comm.).

Two other significant dinocysts make their appearance in Borehole 81/43. Aldorfia dictyota (Cookson & Eisenack) Davey occurs between 92.80m and 90.00m; Kleithriasphaeridium porosispinum Davey occurs between 90.80m and 90.00m. Together with the other recorded dinocysts, these taxa fix the 81/43 sequence between the Scitulus and Pallasioides zones. The uppermost sample examined, at 90.00-90.10m (CSB 4784), yielded a mixed Kimmeridgian and Ryazanian (Early Cretaceous) assemblage including Hystrichodinium voigtii (Alberti) Davey, Dingodinium spinosum (Duxbury) Davey, D. albertii Sarjeant, Gochteodinia villosa (Vozzhennikova) Norris and Scriniodinium pharo (Duxbury) Woollam & Riding. This mixing clearly results from interburrowing at the unconformable junction with the overlying Speeton Clay.

Woollam & Riding's (1983) dinocyst zonation for the English Jurassic was based on a study of a number of sections and cored reference sequences for which there was the best possible ammonite-based stratigraphic control, together with selected already published data. Their zonal boundaries were defined by the appearance and/or extinction of certain key dinocyst taxa. Using these key taxa and the ranges discussed above, Woollam & Riding's zonation can be applied to the present boreholes with relative ease.

The oldest strata in Borehole 81/41 belong to Subzone a of the Gonyaulacysta jurassica-Scriniodinium crystallinum (Gj/Sc) Zone. This is the interval between the appearance of G. dimorphum and the extinction of C. polonicum; the latter occurs between 55.80m and 55.90m. Subzone b extends from this depth up to the appearance of D. tuberosum (between 48.35m and 49.40m) and Subzone c extends from there to the extinction of S. crystallinum (between 24.00m and 25.00m). The succeeding Scriniodinium luridum (Sl) Zone extends from this depth in Borehole 81/41 through the complete sequence of Borehole 81/49 to the extinction of S. luridum between 17.00m and 18.00m in Borehole 81/47. The remaining part of Borehole 81/47 and all the Borehole 81/43 sequence belong to the next youngest Glossodinium dimorphum-Dingodinium tuberosum (Gd/Dt) Zone. The absence of Egmontodinium polyplacophorum Gitmez & Sarjeant prevents the recognition of Subzones a and b.

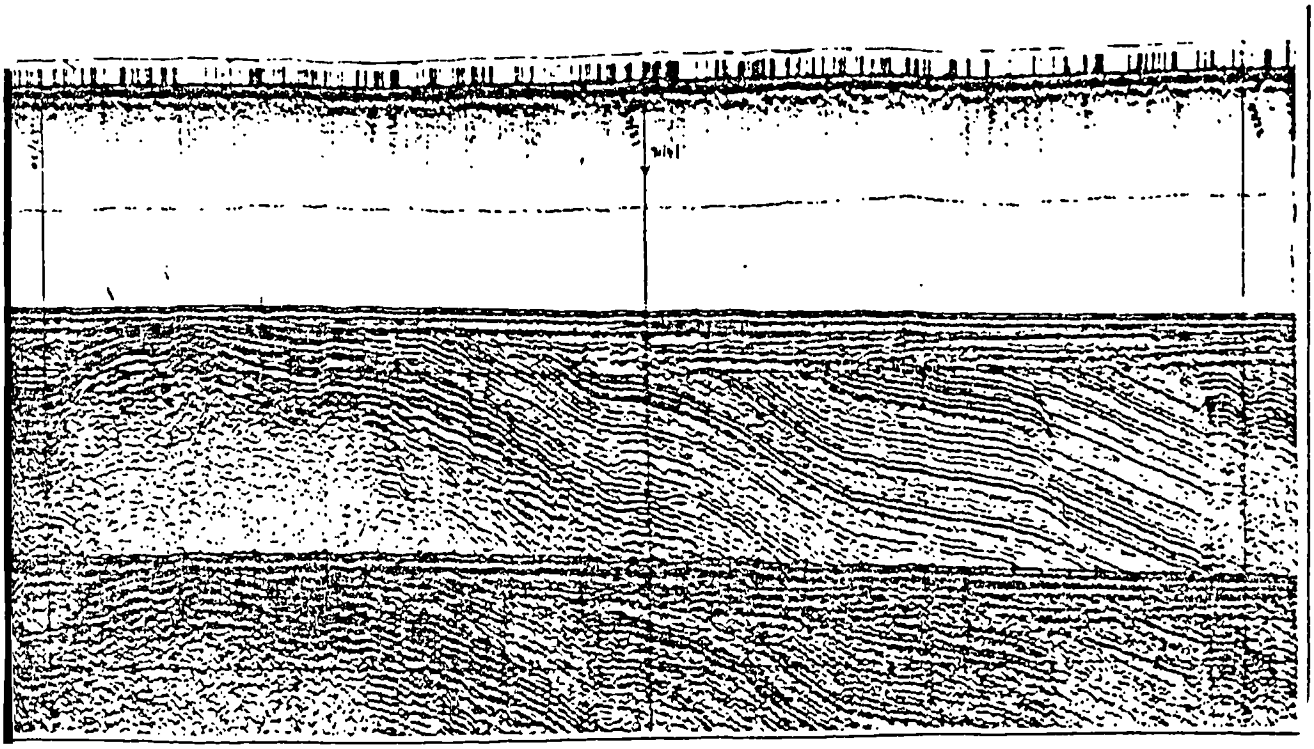
For the North Sea boreholes, the relationship of these dinocyst zones to the standard ammonite-based sequence does not agree, in detail, with that given in Woollam & Riding's (1983) original paper. This disparity is partly explained by the extended ranges of certain key taxa such as D. tuberosum, S. crystallinum and S. luridum recorded in these boreholes, the absence of others such as Rigaudella aemula (Deflandre) Below and the relatively delayed appearance of *A. jurassica*. Reworking cannot be invoked to explain the extended ranges of *S. crystallinum* and *S. luridum* but contamination arising from impregnation of the core with drilling mud must be considered. However, the disparity may be a reflection of genuine diachronism of the dinocyst zones and indicates that Woollam & Riding's (1983) zonation may stand revision as more Kimmeridgian sequences are studied in detail. For example, the extended ranges for *D. tuberosum* and *O. balia* recorded in Borehole 81/41 are endorsed by records of these two taxa in proven Upper Oxfordian Rosenkrantzi Zone of the Harome Borehole, North Yorkshire (Thomas, in prep.).

4. DISCUSSION

Although each of the four boreholes proved only a small part of the Kimmeridgian sequence, taken together they show that there is a normal English development of Kimmeridge Clay in this part of the North Sea Basin. The individual sequences compare closely in lithologies and macrofauna with those of onshore southern and eastern England. The cores include representatives of all the Kimmeridgian zones from Baylei to Hudlestoni (Fig. 2) and, in terms of the stage nomenclature traditionally used in the North Sea Basin, Borehole 81/47 cored a sequence through the Kimmeridgian-Volgian stage boundary. The alternative stage nomenclatures in use for this final part of the Jurassic System are embroiled in the literature of many years past and still lead to confusion. Ammonite provincialism in the Late Jurassic has resulted in the use of three different stage names (Portlandian, Tithonian, Volgian) for the post-Kimmeridgian part of the Jurassic. The situation is further complicated by the dual interpretation possible for the Kimmeridgian and Portlandian stages arising from an ambiguity in their original definitions (see discussion in Cox & Gallois 1981, pp. 25-28). For North Sea geologists, the most unfortunate aspect is that the term Kimmeridgian, and substages thereof, can have two different meanings. In the fullest sense (≡ sensu anglico), it covers the Baylei to Fittoni zones inclusive; in the restricted sense (≡ sensu gallico), it covers the Baylei to Autissiodorensis zones inclusive. For the North Sea area, if Volgian is used as the terminal Jurassic stage name, then Kimmeridgian is almost certainly used in the restricted sense. If Portlandian is used instead, then the Kimmeridgian is probably, but not automatically, used in its fullest sense. It is clearly essential that any author or report should indicate precisely which terminology is used.

The details of the facies and thickness relationships of the Kimmeridgian sequences on the onshore East Midlands Shelf are now well known following study of cored boreholes such as those in the Wash area (Gallois & Cox 1974, 1976; Gallois 1979a) and at Nettleton Bottom, Lincolnshire (Bradshaw & Penney 1982; BGS unpublished data), and the integrated study based on geophysical logs (Penn, Cox & Gallois 1986). Compared with these sections, boreholes 81/41 and 81/43 proved sequences of a comparable order of thickness to that at Nettleton; boreholes 81/47 and 81/49 proved thicknesses which were between double and treble those at Nettleton. Zonal thicknesses at Nettleton (based on study of the collected specimens, core residues, lithological log and geophysical logs) are as follows - Baylei Zone 4.48m, Cymodoce Zone 28.39m, Mutabilis Zone 28.79m, Eudoxus Zone 36.49m, Autissiodorensis Zone 14.52m, Elegans Zone 2.64m, Scitulus Zone 4.89m, Wheatleyensis Zone 8.25m, Hudlestoni Zone 6.20m seen.

The thickness relationships of the offshore boreholes fit in well with the known disposition of the Sole Pit Basin, with boreholes 81/47 and 81/49 occupying a position nearer the centre of deposition (Fig. 1). Part of this basin is shown on the seismic profile through the site of Borehole 81/41 presented in Fig. 7. The faults which apparently affected the sequence at this site do not appear on the N-S profile and are therefore presumed to be striking in a N-S direction. Figure 7 also highlights a disparity between onshore and offshore lithostratigraphical nomenclature. The main seismic reflector in Fig. 7 is identified as the Kimmeridge Clay-Corallian formational boundary. From the 81/41 core (Fig. 3), we know that the so-called "Kimmeridge Clay" includes at its base a thickness of Ampthill Clay and the so -called "Corallian Formation", although representing a single mappable unit in terms of offshore seismic mapping, lumps together several units which



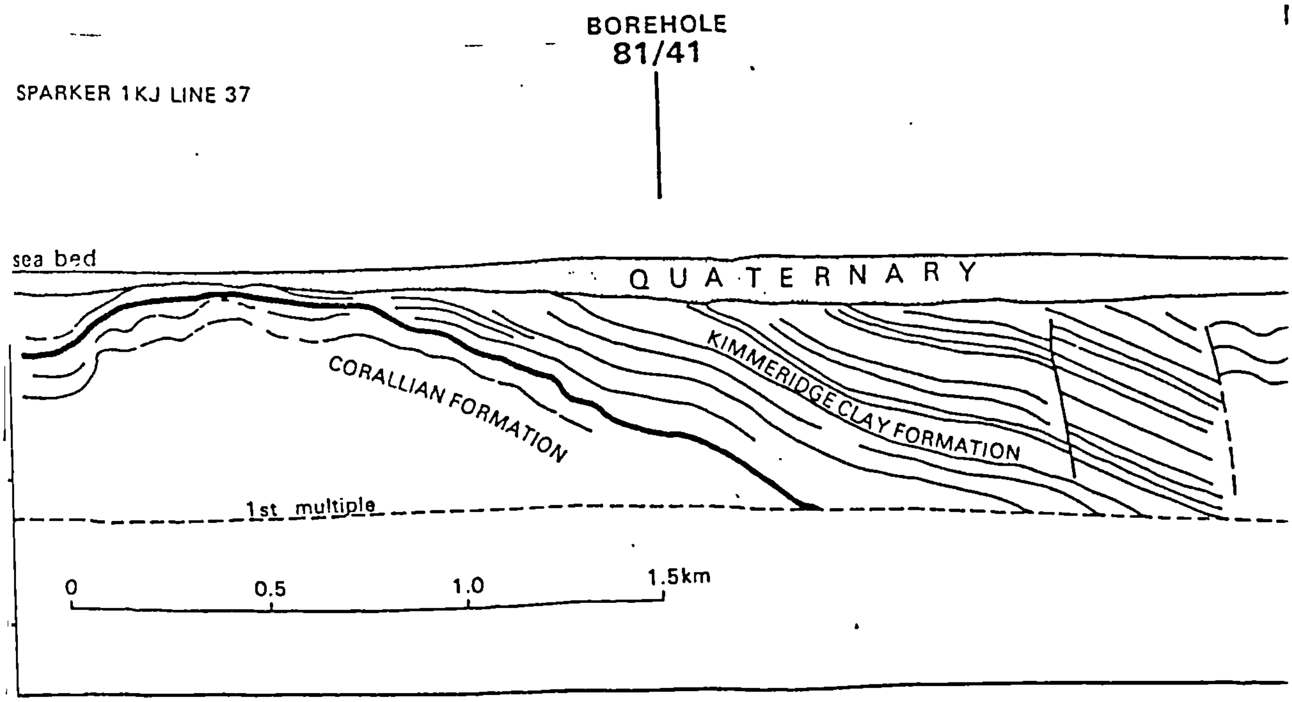

BOREHOLE
81/41
SPARKER 1KJ LINE 37
sea bed
QUATERNARY
CORALLIAN FORMATION
KIMMERIDGE CLAY FORMATION
1st multiple
0
0.5
1.0
1.5km

Fig. 7

onshore are mapped as separate formations; onshore, the latter formation is therefore ranked as a Group. These disparities are straightforward and may be considered academic, but they can lead to misunderstanding in any dialogue and even obscure real geological relationships.

Facies and thickness relationships in the Kimmeridgian of the Cleveland Basin of Yorkshire are less well known. All the Kimmeridgian zones from Baylei to Pectinatus are present and zonal thicknesses, at least in the western half of the Vale of Pickering, are known to be substantially greater than, for example, those at Nettleton. In addition to the transitory exposures in Filey Bay (Autissiodorensis-Elegans zones and Pectinatus Zone; Callomon & Cope 1971, pp. 161-162; Cope 1974b, pp. 213-214) and the pits near Marton (Eudoxus Zone and Wheatleyensis-Pectinatus zones; Cope 1974b, pp. 214-217 emend. Cope 1980, p. 84), there are a number of cored boreholes for which provisional zonal thicknesses are available. Two boreholes drilled by the Yorkshire River Authority at Harome [SE 653810] and at Cliff House near Marton [SE 759842] in 1972-3 (Reeves, Parry & Richardson 1978) together proved the Baylei Zone (c 18m), Cymodoce Zone (c 37m), Mutabilis Zone (c 49m) and most of the Eudoxus Zone (c 79m seen). A borehole drilled alongside the Golden Hill Pit at Marton [SE 72308285] in 1978 for Phase 2 of the BGS investigation into oil shale resources proved (together with the pit section) the Eudoxus Zone (c 89m), Autissiodorensis Zone (c 18m), Elegans, Scitulus and Wheatleyensis zones (c 55m combined), Hudlestoni Zone (c 32m) and Pectinatus Zone (c 6m seen) (Gallois 1979b, p.60, Fig. 6). All these thicknesses are provisional, pending detailed study of the cores. The figure of 340m given in Table 2 of Reeves, Parry & Richardson (1978, p.255) for the thickness of Lower Kimmeridge Clay in the western end of the Vale of Pickering is clearly a mistake. The total Kimmeridge Clay is c 305m, the Lower Kimmeridge Clay c 210m.

The figure of 385m given for the thickness of the Kimmeridge Clay in the Fordon No. 1 Borehole (10 km W of Speeton; Falcon & Kent 1960) and since used for the Yorkshire sequence in general (Cope 1974b, p.211; 1980, p.83) is seriously awry. This thickness is based on the position of the Speeton Clay-Kimmeridge Clay boundary at 1060 ft [323.1m] given by Falcon & Kent (1960, p.29). Specimens in the BGS collections (nos Bq 9378-9476) from 1323 ft [403.3m] to 1430 ft 9 in [436.1m] show this interval to be in Speeton Clay; the latter formation is thus substantially thicker and the Kimmeridge Clay substantially thinner than generally understood. Micropalaeontological work by Dilley, quoted by Neale (1968, p.332) and Neale in Rayner & Hemingway (1974, p.232), had already suggested that the Speeton Clay in this borehole may be 1200 ft [366m] in thickness (i.e. 230m thicker than Falcon & Kent's account). However, because of the obscurity of this fact as a published statement, the implication regarding the Kimmeridge Clay thickness has not been generally appreciated.

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FIGURE CAPTIONS

1. Geological sketch map showing the position of the four North Sea boreholes and onshore localities cited in the text.

2. Stratigraphic position of boreholes 81/41, 81/43, 81/47 and 81/49 in terms of zones and stages.

3. Borehole 81/41 : the zonal and bed-numbered Kimmeridge Clay sequences plotted against the gamma-ray log.

4. Kimmeridgian macrofossils. (full caption to be added)

5. Range of occurrence of selected ostracod taxa recorded in boreholes 81/41, 81/43, 81/47 and 81/49.

6. Range of occurrence of selected dinocyst taxa recorded in boreholes 81/41, 81/43, 81/47 and 81/49.

7. North-south seismic profile through the site of Borehole 81/41.