University College, London.

THE LATE OXFORDIAN TO KIMMERIDGIAN HISTORY OF THE ROB ROY AND IVANHOE FIELDS, OUTER MORAY FIRTH.

By

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To Neil Preston.

"Every opinion based on scientific criticism I welcome. As to the prejudice of so called public opinion, to which I have never made concessions, now as aforetime the maxim of the great Florentine is mine:

'*Segui il tuo corse, e lascia dir le genti.*'* "

Karl Marx, 1867.

* "Go thy way, and let people talk."

Dante, *The Divine Comedy.*

For Helen and Richard

ABSTRACT.

A biostratigraphic anomaly posed by the co-existence of characteristic Late Oxfordian dinoflagellate cyst floras and Kimmeridgian ammonites in the Humber Group of the Outer Moray Firth is thoroughly investigated. Fossils from ten sequences in U.K. Blocks 15/21a and 15/22 cored by Amerada Hess Ltd. are compared with those from onshore Late Oxfordian to Kimmeridgian sequences at South Ferriby (South Humberside), Eathie (Cromarty), and between Brora and Helmsdale in the Moray Firth. The results indicate that the key dinoflagellate cyst marker species *Scriniodinium crystallinum* (Deflandre) and *Endoscrinium galeritum* (Deflandre) have ranges extending into younger sediments than previously supposed; both are recorded in the Mutabilis Zone of the Northern North Sea.

Ammonite faunas collected from both the North Sea wells and onshore provide support for an informal subzonation of the Cymodoce and Mutabilis Zones of the Sub-Boreal Kimmeridgian. This detailed biostratigraphic control is applied to give precise definition of the timing of transgressive and tectonic events and their relationship to resultant sedimentary responses.

The "I Shale" Transgression is demonstrated to be basal Kimmeridgian in age, and the Kimmeridge Clay transgression is dated as early Eudoxus Zone. It is considered likely that the Kimmeridge Clay transgression accompanied the onset of Late Cimmerian tectonism within the Witch Ground Graben, and a Eudoxus Zone age is suggested for this event.

By comparison with East Greenland sections an assessment is made of the degree of overprinting of regional sea-level events by local tectonic events. The conclusions are important in the construction of a depositional model for the reservoir sands of the area.

The Late Oxfordian to Kimmeridgian History of the Rob Roy and Ivanhoe Fields, Outer Moray Firth.

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PART 1 - INTRODUCTION AND OVERVIEW

1. INTRODUCTION.

During the discovery and development of the Ivanhoe and Rob Roy Fields in Block 15/21a of the U.K. sector of the North Sea, cored wells through the Upper Jurassic Sgiath and Piper Formations (Humber Group) yielded well preserved ammonites, as well as palynomorphs. Prior to the commencement of this study, examination of the ammonites suggested a Kimmeridgian (*sensu gallico*) age for the oil-bearing part of the sequence, which consultancy companies consistently dated as Late Oxfordian and earliest Kimmeridgian (Baylei Zone) on micropalaeontological evidence. In 1987 the 15/21 Group at Amerada Hess proposed the creation of a research studentship to be based at University College, London, with the primary objective of investigating the biostratigraphy of both groups to resolve the anomaly.

Cores from nine wells in Block 15/21a and one in Block 15/22 were made available in London and Aberdeen by Amerada Hess Limited. These have been examined in detail and substantial collections of ammonites recovered; the matrix surrounding them was analysed for palynomorphs using standard techniques.

To serve as controls for the biostratigraphy, onshore sections at South Ferriby (South Humberside), between Brora and Helmsdale on the Moray Firth coast, and at Eathie, Cromarty were examined. The South Ferriby section in particular exposes Upper Oxfordian to lower Kimmeridgian mudrocks rich in ammonites and dinoflagellate cysts. It is used as a standard by some service companies, and a detailed section was described.

The opening part of the thesis reviews previous interpretations of the tectonic and sedimentary history of the area, and summarises the various depositional models which have been proposed for the Humber Group in the Outer Moray Firth. Part 2 comprises the database. The sections are described and the locations of the wells given, with a brief review of the preparation techniques used. The stratigraphically important dinoflagellate cyst species and all the ammonite species encountered are systematically discussed with additional remarks on their ranges where appropriate.

Part 3 draws on this data-base and previous work. The biostratigraphic framework and the results of the biostratigraphic study are presented and discussed in relation to the anomaly. With strict biostratigraphic control precise correlation between Rob Roy and Ivanhoe and other Fields in the area is possible, and the timings of tectonic events and their sedimentary results are more clearly understood. Thus, the ultimate objective has been to establish a model for the Late Jurassic history of the area combining biostratigraphical, sedimentological, structural, and palaeoecological evidence.

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2. OVERVIEW.

2.1 REGIONAL TECTONIC SETTING

Structural Evolution.

The structural evolution of the North Sea area was dependent to a considerable degree upon events which occurred beyond its boundaries. The most important of these are listed in chronological order below, with comments on their effects on the area. Prior to the late Silurian Caledonian Orogeny, the North Sea area was widely fragmented in parts of the Iapetus Ocean and Tornquist Sea, and their flanking continental areas. Possibly as a result of adjustments between the formerly separate Laurentian and Scandinavian cratons, rifting was initiated in the Devonian-Carboniferous, illustrated by Devonian movement along the Great Glen Fault, and Carboniferous Variscan topography. The Variscan Orogeny marked the closure of the southern Ocean Proto-Tethys and the formation of Pangaea. The inception of the North-South trending Viking and Central Graben system followed early Permian subsidence of the Moray Firth and East-West trending Northern and Southern Permian Basins. These grabens began rapid subsidence during the Triassic, reaching their maximum structural development by the beginning of the Cretaceous.

Domal uplift and erosion was centred over the Central Graben axis during the Mid-Jurassic. Late Jurassic to earliest Cretaceous strike-slip movements and fault-block rotations in the Viking and Central Graben areas coincided with the opening of the Central Atlantic; the duration of an active Viking-Central Graben system was synchronous with the separation of Pangaea into North America/Europe and Africa. The end of the graben development was affiliated to the onset of sea-floor spreading in the North Atlantic Ocean, initially along the line of the Rockall-Faeroes Trough, shifting to its present axis in the early Tertiary (Glennie, 1984).

Superimposed was an overall northward passive drift of the continents, taking the southern North Sea area from south of the equator in pre-Carboniferous times to over half way to the North Pole today. The combination of time and latitude-related climatic changes and the structural deformation, erosion and sedimentation is responsible for North Sea oil and gas reservoirs ranging in age from Devonian to Tertiary; in the northern and central North Sea Basins most oil and gas is sourced from the Late Jurassic - Earliest Cretaceous Kimmeridge Clay.

Jurassic strata in the North Sea occur mainly in fault-bounded basins related to the regional crustal extension of the graben system initiated in the Permian. Fault-controlled subsidence, contemporaneous with sedimentation, had an important influence on stratigraphic thicknesses and facies during the Late Jurassic.

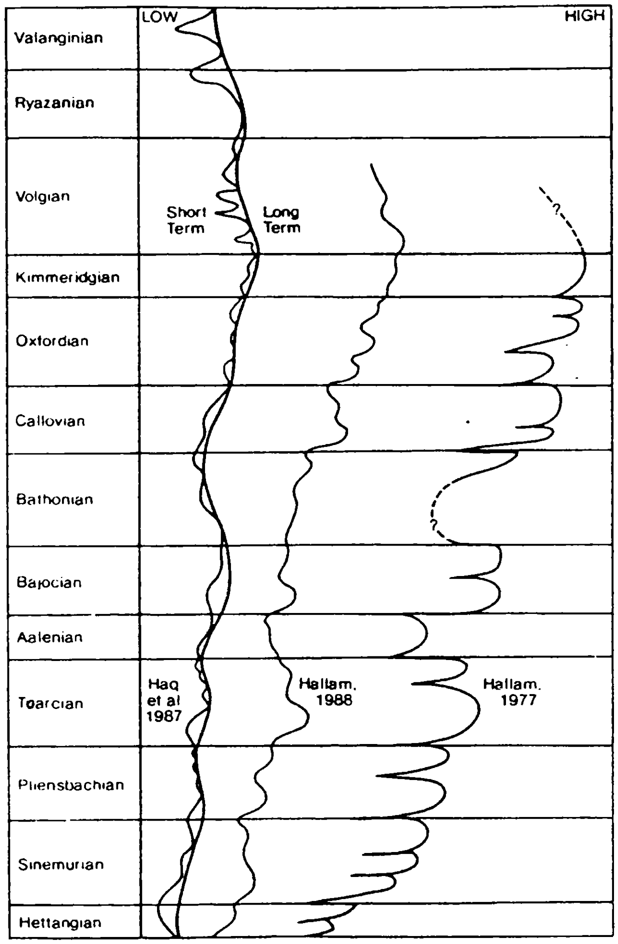
The location of a Middle Jurassic volcanic pile (the Rattray Volcanic Formation) at the intersection of the Outer Moray Firth Basin, the Central Graben and the South Viking Graben led to speculation that the origin of the graben system was plume-generated uplift; the three basins as arms of a failed triple junction (Woodhall & Knox, 1979, etc.). More recently, anomalously thin continental crust under the main grabens has been interpreted as indicating regional lithospheric stretching (after McKenzie, 1978), most rapidly during the mid-Jurassic associated with basaltic volcanism (Wood & Barton, 1983).

Superimposed upon these tectonic effects, eustatic sea-level change was an important influence on Jurassic sedimentation and stratigraphy. Hallam (1978) charts a progressive pulsed sea-level rise until the Kimmeridgian, and Rawson and Riley (1982) point to a change from transgressive to regressive conditions in the North Sea in the latest early Volgian. Isostatic crustal subsidence in response to loading with sediment or water may mask the effects of eustatic sea level changes on crustal movement (Glennie, 1984). An early Kimmeridgian global highstand in sea-level (Vail *et al.*, 1977, and others) was superimposed on subsidence related to the formation of source rocks within the Viking and Central Grabens (Fig. 1.1).

2.2 THE OUTER MORAY FIRTH BASIN.

Regional Structural Elements.

The Moray Firth Basin extends from the intersection of the Central and Viking Grabens in the east, to the Scottish coast (where shore outcrop is Jurassic) in the west (Fig. 1.2). The northern boundary is formed in part by the fault-bounded "high" of the Devonian Caithness Ridge; in the east the Dutch Bank Basin (an embayment in the Devonian granites of the East Shetland Platform) extends the basin area northwards. The southern margin is formed by the Peterhead Ridge - a basement "high" trending NE-SW, and further east by the Buchan and Glenn



Relative sea-level curves for the Jurassic and earliest Cretaceous. All indicate an overall eustatic rise in sea-level during the Late Jurassic with short-term deflections relating to tectonic controls of relative sea-level.

Fig. 1.1. Sea-level curves to show the Early Kimmeridgian global highstand.

Horsts, Devonian granite blocks. The Jurassic Basin narrows in the east due to southward projection of the Fladen Ground Spur (also Devonian). The most prominent structural element within the Moray Firth is the E-W trending Halibut Horst - upfaulted Devonian with an Upper Cretaceous chalk cover.

On the basis of structural style and stratigraphical succession, the Moray Firth Basin is divided into an Inner and an Outer Basin across an axis trending north-south through the central part of Quadrant 13 (Barr, 1985). The Outer (eastern) Basin, in particular the NW-SE trending Witch Ground Graben, is underlain by anomalously thin continental crust; the Inner (western) has a more normal thickness. Dextral transcurrent displacement along the Great Glen Fault led to limited extension and basin subsidence in the western Moray Firth (McQuillin *et al.*, 1982).

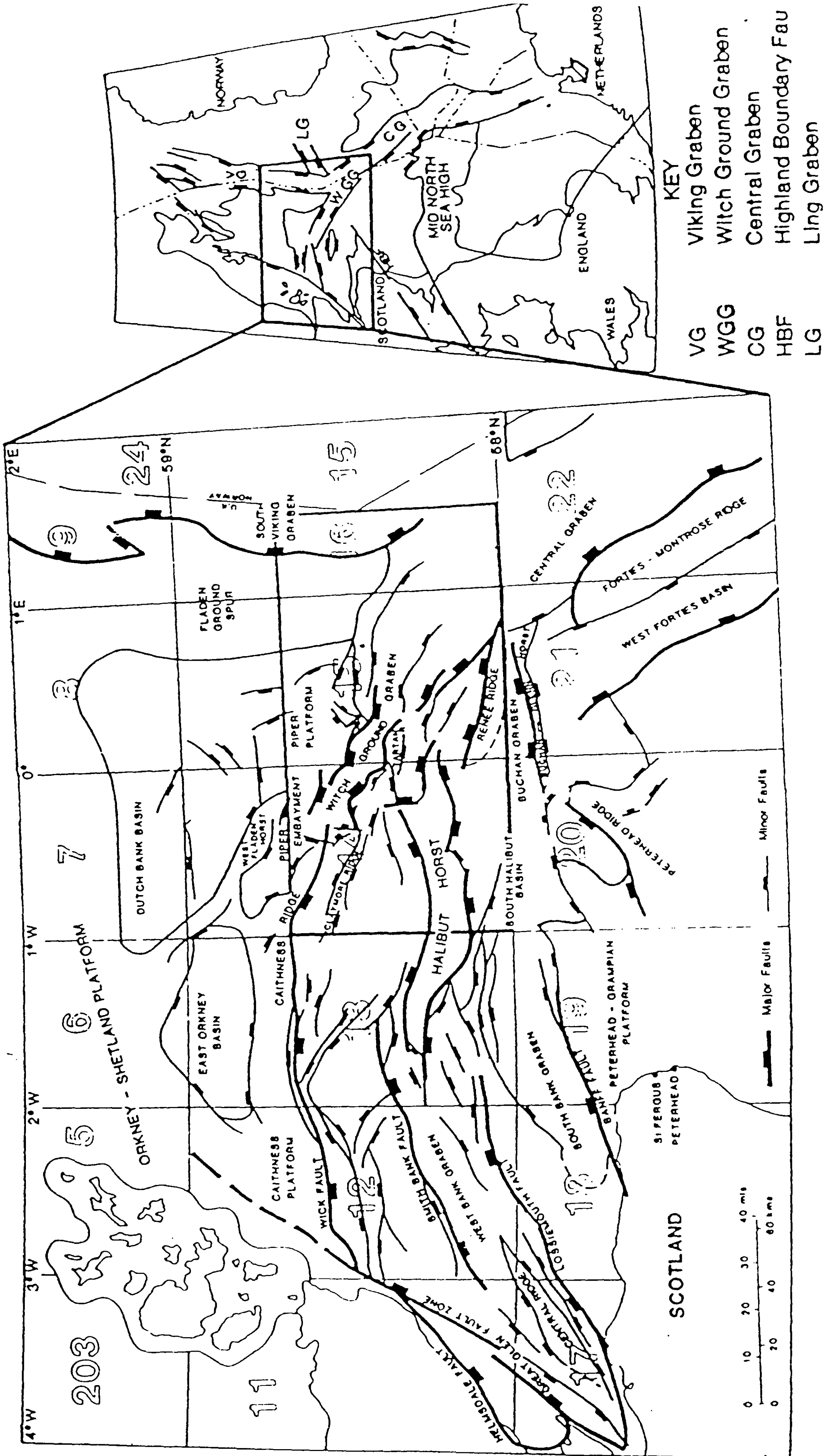


Fig. 1.2. The Moray Firth: Structural elements. From Boldy & Brealey (in press).

The Witch Ground Graben.

The Witch Ground Graben is a Northwest-Southeast extensional basin. Extension subsidence may have occurred during the Permian and Triassic, but is most conclusively recorded by Upper Jurassic and Lower Cretaceous sequences (Beach, 1984). Systematic development of stratigraphic breaks and sediment thicknesses can be related to the fault-controlled geometry of the basin. Stratigraphic truncation and onlap results from asymmetric subsidence due to extension on listric normal faults along the southwest margin with downthrow to the northeast (Amerada Hess, 1987).

The Witch Ground Graben is bordered on the southwest by the Halibut Platform, the Halibut Horst, and the Renee Ridge, and on the northeast by the Piper Platform and the Fladen Ground Spur (Fig. 1.3). The Witch Ground Graben was the major depocentre in the Outer Moray Firth Basin during the Late Jurassic. Thicknesses vary greatly throughout the area, due to differing syndepositional subsidence rates and to post-depositional erosion on uplifted fault blocks. Generally the sequence is thickest on the downthrown sides of faults in the southwest, and thinnest on the less-faulted Fladen Ground Spur flanks in the northeast (Turner *et al.*, 1984).

2.3 REGIONAL JURASSIC STRATIGRAPHY AND FACIES.

Stratigraphic Evolution (Jurassic).

Lower Jurassic deposits are mostly absent over the eastern Moray Firth, Central Graben, South Viking Graben and northwestern Norwegian Danish Basin probably due to upwarping of the central North Sea and erosion during the mid-Jurassic (Brown, 1984). Where present they are transgressive, argillaceous and marine.

Middle Jurassic, arenaceous strata deposited in non-marine to paralic environments are more widespread. Hydrocarbon reservoirs formed where sands shed from the updomed central North Sea and marginal platforms accumulated in adjacent basins. In the extreme north and parts of the southern North Sea, marine conditions persisted, reintroduction becoming more widespread at different times.

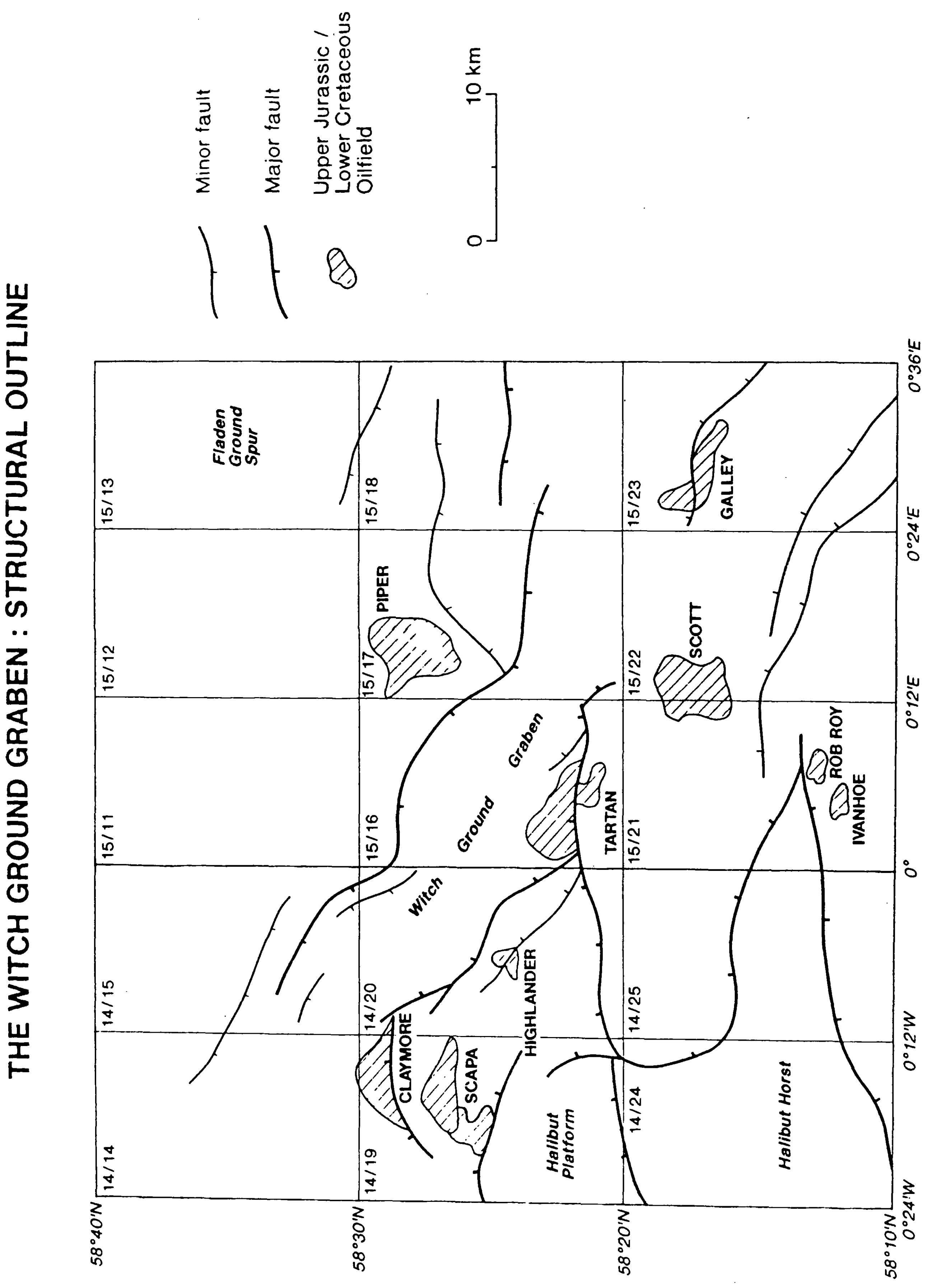


Fig. 1.3. The Witch Ground Graben: Structural elements.

Over most of the North Sea the Upper Jurassic consists of dark, marine argillaceous deposits, but also includes important reservoir sands; shallow-marine, transgressive sediments are widespread in the Outer Moray Firth Basin.

Subsequent to deposition of thick Upper Palaeozoic non-marine sequences, terminated by the Hercynian Orogeny, sedimentation recommenced in the Early Permian with deposition of continental red-bed sequences, and this cycle of non-marine sedimentation continued throughout the Triassic. The area was finally transgressed during the Lower Jurassic with deposition occurring in shallow shelf seas. In the late Early to early Middle Jurassic there was in an important phase of thermal up-doming of the Outer Moray Firth, resulting in widespread erosion. This Mid-Cimmerian uplift terminated the second basin-fill sequence and culminated in the formation of the Central North Sea Dome, the subsequent collapse of which was accompanied by the formation of rift valleys containing extensive volcanics. The Outer Moray Firth was finally submerged by the sea during the Oxfordian (Amerada Hess, 1987).

Onshore, the Early to Middle Jurassic sediments show a broadly transgressive-regressive-transgressive sequence. Shallow marine, stable-shelf sedimentation continued to the Oxfordian, but reactivation of the Helmsdale Fault led to deposition of marine gravity flow sandstones and debris flows during the Kimmeridgian and Volgian. The youngest Jurassic rocks cropping out onshore are Kimmeridgian to mid-Volgian strata. They consist of the Kintradwell Boulder Beds at the base, the Allt na Cuile Sandstones, and the Helmsdale Boulder Beds, in which coarse breccias, conglomerates and sandstones (Linsley, 1972), deposited by diverse gravity flow processes, are interbedded with dark basinal marine shales (Brown, 1984) at the top of the sequence.

The Inner Moray Firth Basin succession described from the Beatrice Field (UK Block 11/30) compares closely with the onshore Lower-Middle Jurassic (Linsley *et al.*, 1980); the Upper Jurassic strata comprise predominantly of shales. In the Outer Moray Firth, the Upper Jurassic, overlying the Middle Jurassic basaltic lavas and tuffs, consists largely of the shallow marine sands of the Piper Formation (Williams *et al.*, 1975). The overlying organic-rich marine shales of Kimmeridgian to mid-Volgian age, are locally interbedded with marine-gravity flow sands derived from fault-controlled "highs", e.g. in the Claymore Field (where they are derived from the Halibut Horst), and locally along the southern margin of the Witch

Ground Graben.

Jurassic Lithostratigraphy.

The oldest Jurassic rocks present in the Outer Moray Firth are the volcanic sequences of the Rattray Volcanic Formation and the time-equivalent paralic sediments of the Pentland Formation; (Fladen Group, Deegan & Scull, 1977). Radiometric dating of the volcanics indicats a Bathonian age (Howitt *et al.*, 1975); biostratigraphic analysis of the Pentland Formation sequences and sediments interbedded with the Rattray volcanics supports this.

No Early Jurassic sediments appear to be preserved in the Outer Moray Firth. Their absence is attributed to their removal during the pre-rift updoming of the Central North Sea area (Eynon, 1981).

In the Outer Moray Firth, the uplift and subsequent collapse of the Central North Sea Dome are responses to the widespread Mid Cimmerian tectonic event, the Fladen Group being deposited during the extension and rifting associated with collapse of the dome. The thickest sequences of the Fladen Group occur in the southern part of Quadrant 15,where in excess of 3,000 m of volcanics have been postulated (Woodhall & Knox, 1979). A major unconformity separates the Middle Jurassic Rattray Volcanics Formation (Fladen Group) from the overlying Upper Jurassic Humber Group (Rhys, 1974). The type area is the Southern North Sea Basin, though the group is widely distributed throughout the North Sea. Thickness varies considerably since the sediments were deposited on a series of tilted fault blocks produced by pre- and syndepositional tectonic activity. Later Cimmerian movements resulted in some erosion in all but the most protected structural positions. In the Central and Northern North Sea it consists largely of dark coloured, marine claystones and shales with areally restricted intercalations of sandstone.

Historically, the Humber Group has been divided into two constituent formations in Block 15/21: the Piper Formation and the overlying Kimmeridge Clay Formation. Recently, Harker *et al.* (1987) redesignated the lower part of the Piper Sand Formation as the Sgiath Formation, a paralic sequence of sandstones, coals, carbonaceous mudstones and siltstones. These are the oldest sediments to overlie the Middle Jurassic Fladen Group in the Outer Moray Firth.

The Late Jurassic rise in sea-level (Vail & Todd, 1981; Rawson & Riley, 1982;

Haq *et al.*, 1987; Surlyk, 1990) is recorded in the Outer Moray Firth by a transition from basal paralic facies into shallow marine/shoreface sands (Piper Formation) and then deeper marine organic-rich shales (Kimmeridge Clay Formation). The Heather Formation (*sensu* Deegan & Scull, 1977) is absent.

Sgiath Formation (Harker *et al.*, 1987). Type Section: UK well 14/19-4 (Occidental) from 8583 ft (2617 m) to 8619 ft (2628 m) below K.B.; Reference Section U.K. well 15/17-4 (Occidental). Distribution: throughout the Witch Ground Graben in UK Quadrants 14, 15, 20, 21, 23.

In the type well the formation consists of medium to coarse-grained quartzose sandstones, interbedded with massive coal beds and thin carbonaceous mudstones and siltstones. Discrete coal beds are discontinuous but the carbonaceous content is a distinctive feature (Harker *et al*, 1987). The top of the Sgiath Formation and base of the conformably overlying Piper Formation is defined by a change in log character from low-gamma-ray sands to higher-gamma-ray mudstones of the marine "I Shale" (Maher, 1980).

Piper Formation (Deegan & Scull, 1977). Type Section: U.K. well 15/17-4 (Occidental) from 8444 ft (2574 m) to 8746 ft (2666 m) below K.B. Distribution: over most of the Witch Ground Graben.

It consists of a series of very fine, fine, medium and coarse-grained marine shelf sandstones of transgressive and regressive nature, with occasional shales marking the more extensive transgressions. The main sandstones are quartzose, well-sorted, and poorly cemented. Bioturbation is common throughout the sandstones but the only preserved macrofossils are concentrations of large bivalves (*Ostrea* sp.) and the odd belemnite near the top of the formation in the type well. However, interbedded shales contain numerous macrofossils including ammonites, bivalves, and belemnites.

The upper boundary is marked by a sharp lithological contact with one of the argillaceous formations of the Humber Group. In the vicinity of the Piper Field, there is a stratigraphic break at the top of the Piper Formation and it is overlain non-sequentially by the Kimmeridge Clay Formation. In more complete sections the Heather Formation may be represented (Deegan and Scull, 1977, Turner *et al.*, 1984; Harker *et al.*, 1987).

Kimmeridge Clay Formation (Arkell,1947). Well Type Section: U.K. well 47/15-1 (Phillips) from 2902 ft (885 m) to 3014 ft (919 m); Reference Section U.K. well 211/21-1A (Shell/Esso). Distribution: one of the most widespread formations in the North Sea, deposited during the Late Jurassic transgression that submerged much of northern Europe. Dark grey-brown to black, non-calcareous claystone, it is characterised by a very high level of radioactivity - a function of organic carbon content. In places sandstone occurs as either very thin interbeds or locally as thick units with only minor shales. The main reservoir of the Claymore Field is such a unit - the Claymore Sandstone Member (Turner *et al.*, 1987), derived from the Halibut Horst.

The upper boundary in most wells in the Central and Northern North Sea is an unconformity (the "Late Cimmerian Unconformity"), normally overlain by Cretaceous sediments of varying age.

2.4 HUMBER GROUP LITHOSTRATIGRAPHY AND CORRELATION: WITCH GROUND GRABEN

Considerable uncertainty exists in the correlation of the Sgiath and Piper Formations from their type section in the Piper Field (Block 15/17) southwestward into Block 15/21 (Fig. 1.4), due in part to poor biostratigraphic control.

Piper Field Sequence, Block 15/17.

In the Piper type well (15/17-4) the Sgiath Formation encompasses the pre-"I Shale" Piper units (Maher, 1980; Turner *et al.,* 1984). The age of these basal sediments was regarded by Maher (1980) to be Callovian. There is, however, no evidence of a hiatus directly beneath the "I Shale", from the lower half of which Maher records unspecified late Oxfordian ammonites. Harker *et al.* (1987) state that marine strata near the top of the Sgiath contain Late Oxfordian dinocysts, with terrestrially-influenced sediments near the base containing less informative spore-dominated assemblages. It is likely that all the Sgiath sediments are also of late Oxfordian age, rather than the Sgiath/"I Shale" boundary representing a period of non-deposition. The "I Shale" occurs 15 m above the base of the Sgiath in 15/17-4, and Sgiath Formation thickness is given as varying from 11 m in its type well (14/19-4) to as little as 4 m, and as much as 56 m, (Harker *et al.*, 1987). The

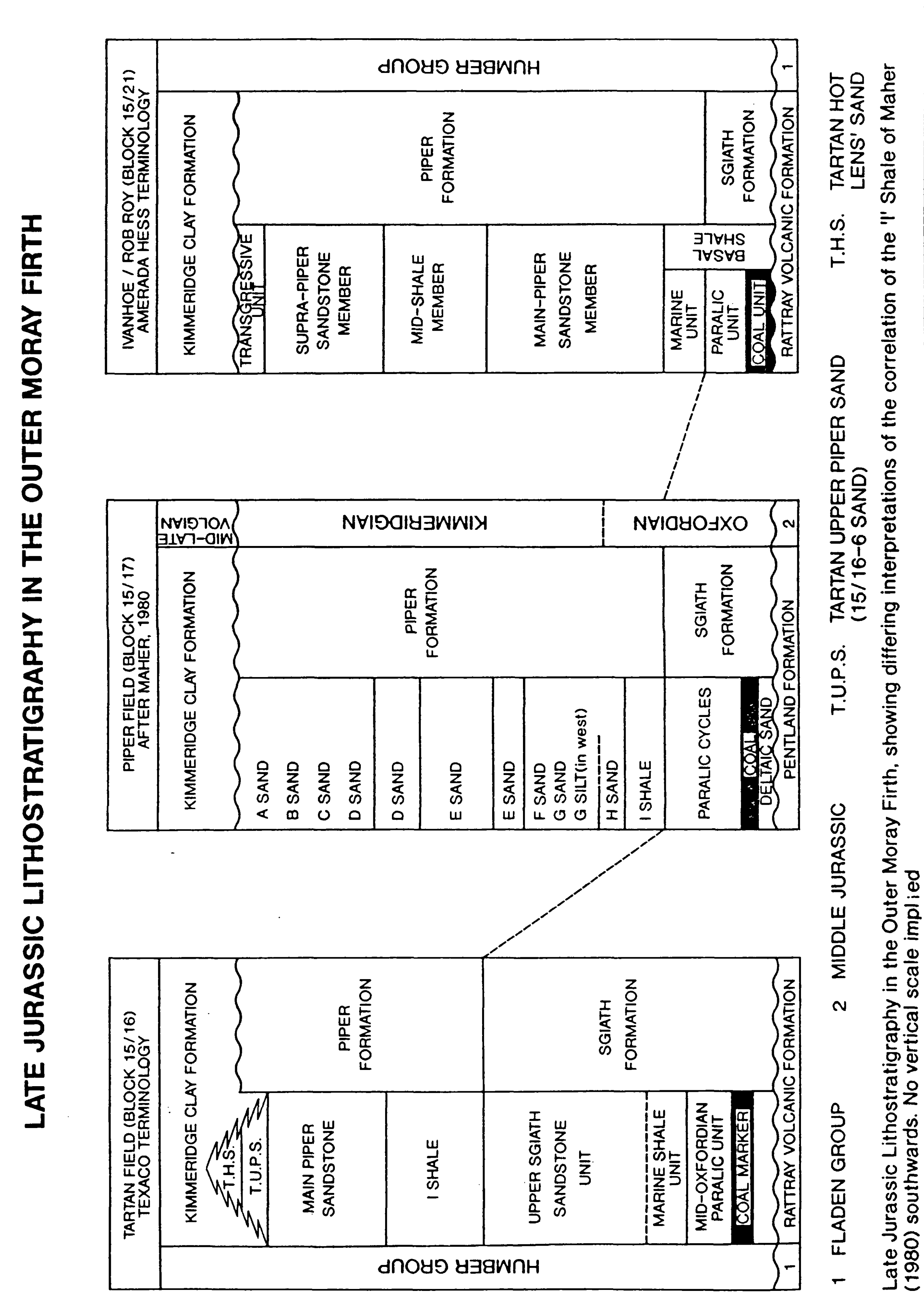


Fig. 1.4. Humber Group correlation: Outer Moray Firth.

Formation is broadly time equivalent to the uppermost part of the Heather Formation in the Central and Northern North Sea.

The base of the Piper Formation is marked by the relatively high-gamma-ray response of the "I Shale". This unit records a significant marine transgression over the Piper area. The Piper Formation grades upward from silt, with plant fragments, coal clasts, pyrite and sandy lenses (15/17-5) into fine-grained, moderately well-sorted, bioturbated sandstone (Maher, 1980). The Formation contains a marine biota of ammonites, bivalves and dinocysts which date it as Late Oxfordian to Kimmeridgian. Williams *et al.* (1975) describe the Piper reservoir as a series of stacked and imbricated barrier-bar and other littoral and shallow marine sand bodies, with the gross reservoir-sequence subdivided into three main sandstone intervals separated by two silty shale intervals which are mapped nearly continuously over the Piper Field.

In the Piper Field there is a stratigraphic break at the top of the Piper Formation; in 15/17-4 it is overlain non-sequentially by Mid-Volgian shales of the Kimmeridge Clay Formation. Further off structure a complete sequence of Kimmeridgian through Volgian sediments is present (Harker *et al.*, 1987).

Tartan Field Sequence, Block 15/16.

O'Driscoll *et al.* (in press) consider 14/19-4 and 15/17-4 to contain condensed sequences, with thicker development of fully marine sand and shale sequences below the "I Shale" occurring in the south of Blocks 15/17 and 15/21. Thus there is a shallow marine sandstone, informally termed the Upper Sgiath Unit Sandstone, with lithological affinities to the Piper Formation, within the Sgiath Formation. The Sgiath Formation is informally sub-divided into a lower paralic "Mid Oxfordian Unit" (46 m) and an "Upper Sgiath Unit" (107 m); reference well 15/17-9.

The "Mid Oxfordian Unit" comprises paralic to deltaic carbonaceous shales with occasional sands and thick coals; unconformably overlying this the Oxfordian to lowermost Kimmeridgian "Upper Sgaith Unit" is described as grey, organic rich, pyritic shale tending to coarsen upwards into lower shoreface and finally upper shoreface delta-front sands. The base of the Piper, marked by deposition of the transgressive "I Shale", is dated as Early Kimmeridgian on dinocysts and ostracods. O'Driscoll *et al.* do note that the "I Shale" is lithologically similar to the basal shale of their "Upper Sgiath Unit" and that without firm biostratigraphic control confusion between the two can arise. The succeeding clean, shallow marine sandstones form the main reservoir unit in the Tartan, Highlander, and Petronella Fields. Deposition of these sands did not reach as far south as the preceding Upper Sgiath Unit; upper shoreface sandstones are developed to the west of the Sgiath depocentre and against the northern side of the Halibut Horst and over Blocks 14/20 and 15/16. These "Tartan-type" sandstones (O'Driscoll *et al.*, in press) are subarkosic to lithic subarkoses (*sensu* McBride, 1963) rather than quartz arenites as in the Piper Field. Over the area from the Tartan and Highlander Fields to Block 15/11, sediment input kept pace with the rising sea level during the late Kimmeridgian and a thick, shale-free, but poorly sorted sand accumulated (the "Upper Piper Sandstone"). This is an important reservoir in the Tartan, Highlander and Petronella Fields where it is termed the "15/16-6 Sandstone Member" (Texaco Ltd.). Additionally, a sandstone with a high gamma-log signature was deposited over the Tartan Field - the "Hot Sand" Member of uppermost Kimmeridgian to Lowermost Volgian age. This is included in the Piper Formation. Almost everywhere else in the basin, Kimmeridge Clay facies were being deposited, except in the Claymore Field, where the equivalent unit is a coarsening-upward, siltstone-sandstone sequence.

Ivanhoe and Rob Roy Sequence, Block 15/21. (Fig. 1.5)

In the Ivanhoe and Rob Roy Fields (southern part of Block 15/21) the earliest Upper Jurassic sediments were deposited under paralic conditions and often contain well-developed coal seams. Below the Kimmeridge Clay Formation the sequence is divided into four members; from the base upwards these are: the Basal Shale Member, Main Piper Sand Member, Mid Shale Member and Supra Piper Sand Member (Amerada Hess Ltd.). A tripartite division of the Basal Shale Member into a lowest Coal Unit, a Paralic Unit and an uppermost Marine Shale Unit can be readily recognised; the lower two of these units were assigned to the Sgiath Formation in this area (Amerada Hess, 1987; Boldy & Brealey, in press) because they represent non-marine sedimentation.

The thickness of the Basal Shale Member varies greatly, from less than ten to over a hundred metres; this was interpreted as indicating that the Basal Shale Member infills hollows upon the eroded Middle Jurassic volcanic surface, with onlap occurring onto volcanic highs (Amerada Hess, 1987). It is likely that the basaltic lavas were much more resistant to erosion than the contemporaneous tuffaceous mudstones, so deeper erosion would be expected where mudstones predominate. This is supported by the observation that the thickest sequences of the Basal Shale Member are seen where the development of basalts within the Middle Jurassic is poorest.

The lower, non-marine part of the Basal Shale Member (i.e. the Sgiath Formation of Amerada Hess) was deposited in lagoonal-marginal marine conditions, with swamp conditions leading to the formation of coal. The Marine Shale Unit represents a major transgression that resulted in a fully marine depositional environment; it has been considered to represent the "I Shale" of the Piper area (current Amerada Hess lithostratigraphic terminology for 15/21). Where this sequence is thickly developed subordinated sandstone interbeds occur up to 3 m thick. These are generally silty and contain marine bivalves, abundant plant debris and rip-up shale clasts. Bioturbation and calcite doggers are widespread. The sandy sequences are interpreted as storm-generated sheet sands, laid down above wave-base in a shallow marine setting. A progressive upward increase in grain size is seen until an amalgamated sand sequence is developed which is recognised as the base of the Main Piper Sand Member (= Upper Sgiath Unit Sandstone of O'Driscoll *et al.*, in press).

The Main Piper Sand Member commences with a coarsening-upward, bioturbated, silty sand containing calcite doggers and occasional wave-generated ripple forms (interpreted as a lower shoreface sequence by Amerada Hess, 1987). Above this lie thick medium to coarse-grained quartzose sandstones with occasional granule grade pebbles. The only sedimentary structures seen are planar cross-stratified foresets and parallel stratification. The quartzose sands are the most common lithofacies and form the best reservoir layers. The coarsest sequences are conglomeratic sands. Some of these are cross-bedded and contain pebbles of extra-formational quartz, quartzite and acid igneous volcanic clasts that are up to 3 cm in diameter. A second type are developed in fining-upward units that contain extraformational clasts plus intraclasts of coal indicating erosive reworking of a back barrier sequence. The other major lithofacies recognised in the Main Piper Sand Member are thin (.3-.6 m) fining upwards sands that commence with a scoured erosive base and pass upward into argillaceous heavily bioturbated sands. These units occur in stacked sequences up to 50 m thick with occasional thin

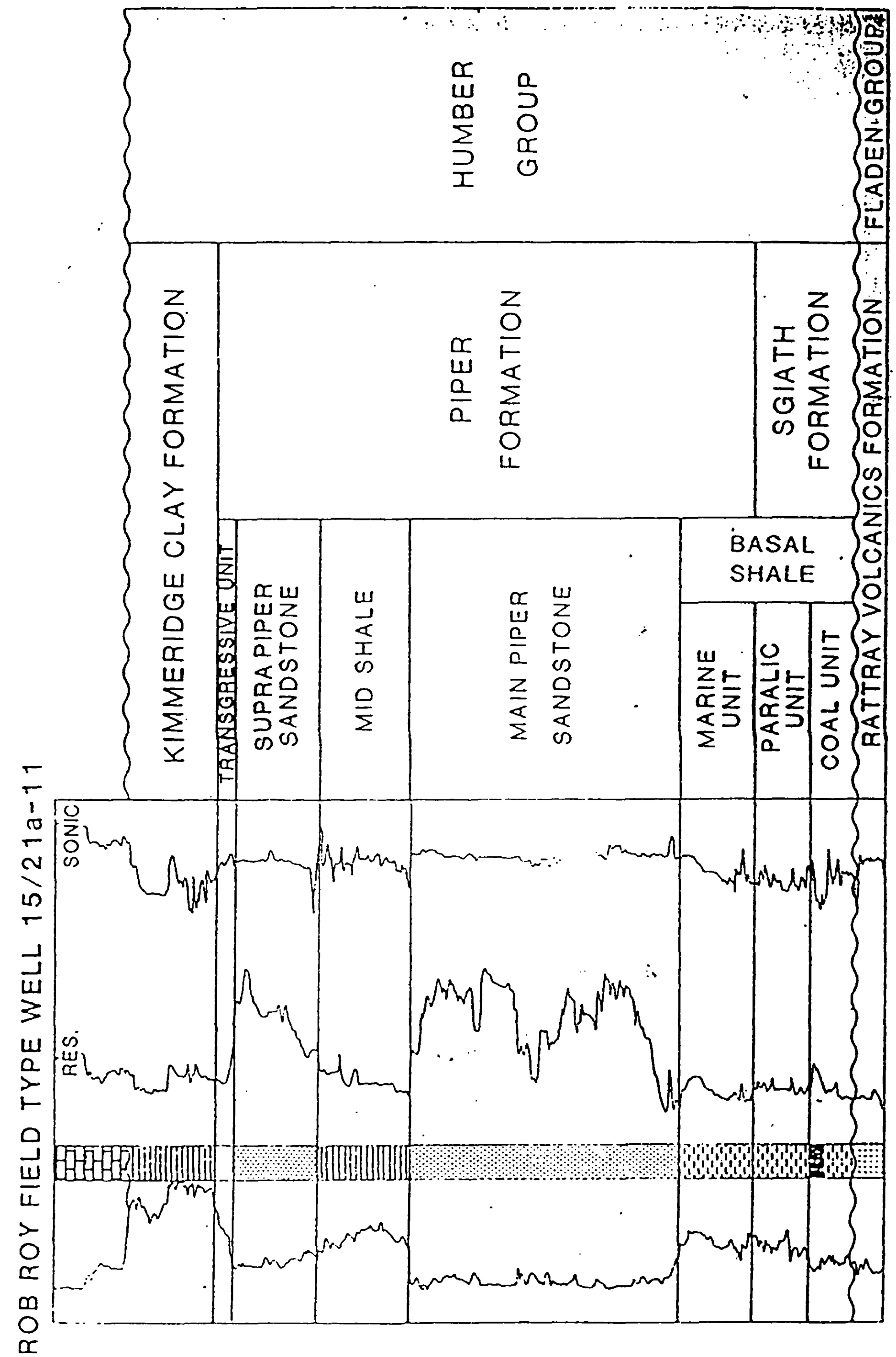


Fig. 1.5. Block 15/21: Late Jurassic lithostratigraphy. From Boldy & Brealey, (in press).

interbedded organic-rich claystones.

Mid Shale Member (= "I Shale" after O'Driscoll *et al.*, in press) deposition recommenced in a fully marine environment, with anoxic bottom conditions suggested by abundant pyritic nodules and high organic content, although there is benthos elsewhere. It is from these low energy marine shales that ammonites have been recovered (by Nicol Morton and the author) which indicate that deposition of the Mid Shale Member continued until mid-*mutabilis* Zone times in contradiction to the micropalaeontological evidence (foraminifera, palynomorphs). A second major coarsening-upward regressive sequence is recognised towards the top with intensely bioturbated, grey, silty clays passing progressively into argillaceous sands, and finally gradationally into the lower shoreface sequence at the base of the Supra Piper Sand Member (= "Main Piper Sand" of O'Driscoll *et al.*, in press). This consists of a single coarsening-upward sequence of medium-fine grained sandstones, significantly richer in detrital feldspar in comparison to the Main Piper Sands (*sensu* Amerada Hess).

The uppermost unit recognized within the Piper Formation is a thin, fining-upward, transgressive sequence (the Transgressive Unit of Amerada Hess). It is overlain by the highly radioactive shales of the Kimmeridge Clay Formation. There is a marked velocity contrast between the relatively high velocity "cold" shales of the Transgressive Unit and the lower velocity "hot" organic-rich shales of the Kimmeridge Clay Formation, giving rise to a variably intense, but widely mappable seismic event (Boldy & Brealey, in press). The boundary between the Kimmeridge Clay and Piper Formations is often a significant hiatus, with the oldest Kimmeridge Clay condensed or even absent altogether. The great variation in thickness of the early Kimmeridge Clay is strong evidence of significant faulting, synchronous with the major transgression that produced Kimmeridge Clay deposition (Boldy & Brealey, in press). The lithology of the Kimmeridge Clay Formation is highly variable in Block 15/21; it contains thick sandstone sequences assigned to the Claymore Member.

As this research was carried out on material from the Sgiath and Piper Formations from Block 15/21a provided by Amerada Hess Ltd., the standard succession used in the body of this work shall be that recognized in this area, with the units renamed, from below; the α Shale, the β Sand, the γ Shale, and the δ Sand. This is designed simply to avoid confusion which may arise from the use of several similar lithostratigraphic schemes in the area (Fig. 1.4).

2.5 DEPOSITIONAL MODELS FOR THE HUMBER GROUP IN THE WITCH GROUND GRABEN

Boote & Gustav (1987) proposed a model of extensive delta systems on the flanks of the uplifted arch of the Central North Sea Graben Province retreating southwards as the arch subsided during the Late Jurassic. As the Witch Ground Graben Province was drowned during the Oxfordian transgression, brackish water lagoons and bayhead deltas of the Sgiath system developed, gradually infilling the uneven topography of the Witch Ground Graben with a succession of minor alluvial and deltaic cycles. Eventually the seaward strandline systems were pushed back southwards, being largely destroyed by shoreface erosion as they retreated.

Towards the end of the Oxfordian the diachronous southwards transgression was temporarily halted as the Piper wave-dominated delta complex prograded back northwards and westwards across the Witch Ground Graben. Two coarsening-upwards cycles (equivalent to the β Sand and the δ Sand) can be distinguished, forming extensive sheet sands passing laterally into marine shale equivalents.

By the early Kimmeridgian regional downwarping had formed a semi-enclosed basin in which circulation was restricted. In the Witch Ground Graben province, the wave-dominated delta complex was abandoned and the strandline system migrated southwards. The Graben began to form a distinct depression; the unlithified cover of rotating fault blocks was locally eroded and redeposited around the emerging structures.

The Graben began to subside rapidly by the Early Volgian; semi-lithified sand was reworked from the flanks of the subsiding depression and was recycled into the basinal lows. In this manner the Claymore and Galley sands were derived from the Halibut Horst and Fladen Ground Spur.

Boote & Gustav's model is broadly in agreement with Turner *et al.* (1984) who proposed a northeasterly progression for the Piper deltaic sand sequences. Progradation would also be considered to have been from south to north on gross isopach considerations and to reflect the regional southward Mid and Late Jurassic transgression over the subsiding Central North Sea Dome (Amerada Hess, 1987).

Conversely, O'Driscoll *et al.* (in press) have proposed that the source area for much of the sand lay to the northeast of the Witch Ground Graben. Their Upper Sgiath Unit sandstone is considered on isopach information to show a well defined north-northeast - south-southwest channel axis and to shale out towards the southwest. The channel axis contains up to 170 m of coarse sandstone with fining-upwards units interpreted as tidally-influenced distributary channel deposits, and medium to coarse grained sandstones interpreted as upper shoreface facies. Turner *et al.* (1987), in discussion of the South Brae Field (Fig. 1.6) attribute a latest Oxfordian or earliest Kimmeridgian age for the initiation of the South Brae fan system, and therefore for uplift of the sediment source, the Fladen Ground Spur. This is also envisaged as the source area for the Upper Sgiath Unit quartz-arenitic sandstones; the Main Piper Sand Member of Block 15/21 is seen as a more distal equivalent of these.

BRAE AREA REGIONAL LOCATION

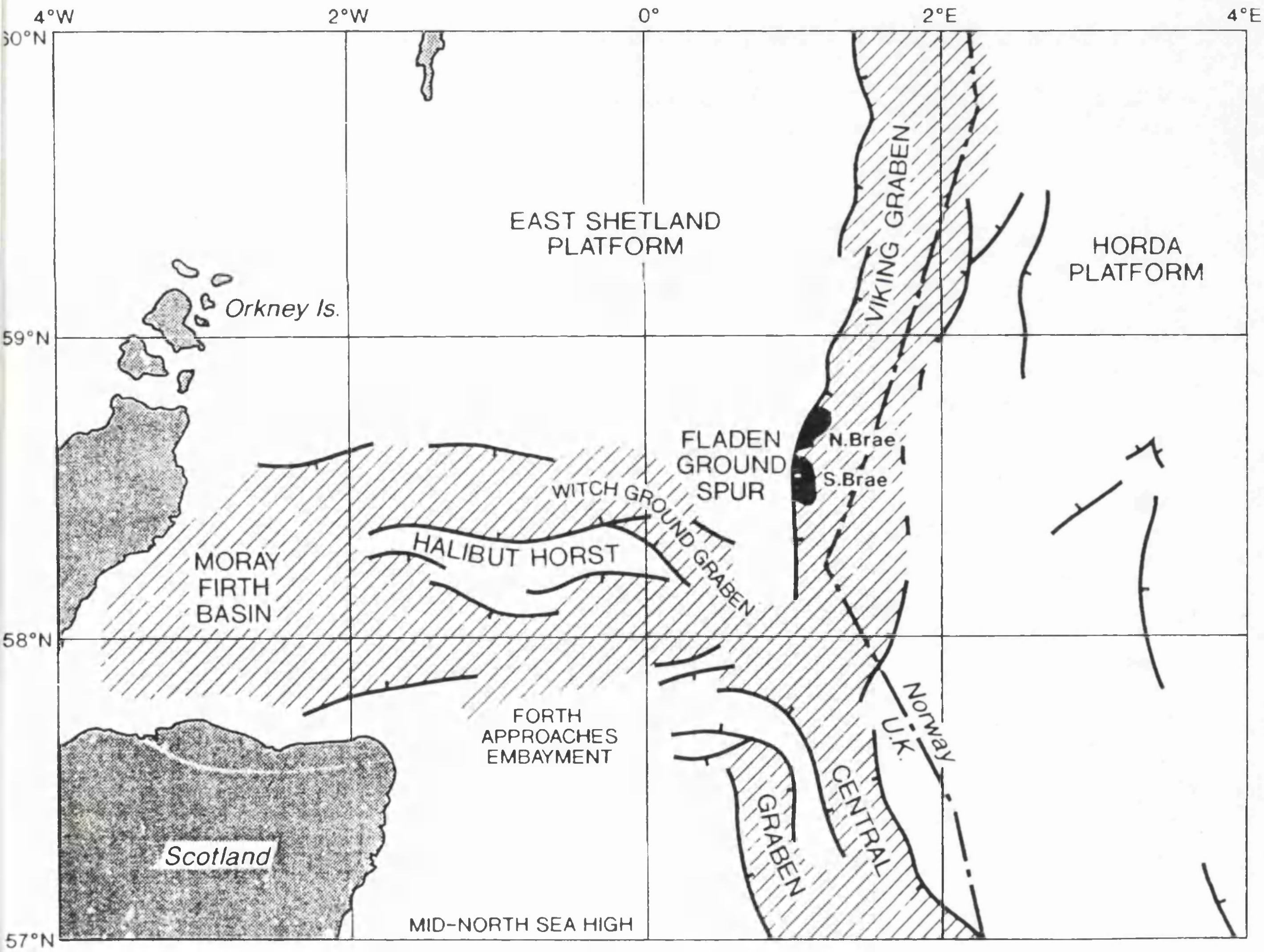


Fig. 1.6. Location of the Brae Fields, Block 16/7a, South Viking Graben.

The model of O'Driscoll *et al.* proposes a southwest to northeast marine transgression over the Sgiath Unit for the "I Shale" (which is correlated with the Mid Shale Member of Block 15/21), supported by a thickening towards the southwest. Subsequently, a delta system once again prograded from northeast to southwest, depositing the Piper quartz-arenitic sands across the Piper Field, with upper shoreface deposition forming the main reservoir units. A separate source is indicated for the Tartan-type sandstones, with more arkosic sands being derived from the Halibut Horst to the southwest following reactivation of the east-west faults bounding its northern margin, depositing the main sands in the Tartan and Petronella Fields.

As marine transgression progressed during the Kimmeridgian, the Piper delta retreated further to the NE; sediment input kept pace with rising sea-level in the Tartan, Highlander and Petronella Fields area however, giving rise to the Upper Piper Sand, or "15/16-6" sandstone Member. With further transgression in the Late Kimmeridgian, upper shoreface facies persisted only close to the Halibut Horst source. A high gamma ray sandstone (the "Hot Sand" Unit) was deposited over the Tartan Field, equivalent to the "Piper" unit in the Claymore area. During the Early Volgian a major subarkosic fan complex developed, as E-W and NW-SE faulting continued, abutting against the Halibut Horst. Distal equivalents of this are found in the Highlander, Petronella and Tartan areas ("Hot Lens" Sandstone Members of the Tartan Field). Turner *et al* (1984) have suggested that the abundance of feldspar in the Tartan area sands infers that they were at least partly eroded from an area of exposed crystalline basement, and propose the most probable source direction is from the southwest, where Devonian sandstones and granitic rocks underlie Jurassic sandstones on the Halibut Horst.

The Amerada Hess (1987) model subdivides the Upper Jurassic strata into two sequences in the Outer Moray Firth; an essentially pre-rift sequence comprising the Sgiath and Piper Formations, and a syn-rift sequence, the first part of which is formed by the Kimmeridge Clay Formation, and which also includes Lower Cretaceous strata. The isopach pattern of the pre-rift sequence mirrors that of the preceding Middle Jurassic and relates to the dying effects of Mid Cimmerian tectonism. The Kimmeridge Clay Formation displays a different pattern with much more rapid thickness variation, and was deposited during the major Late Cimmerian phase of extension that affected the Outer Moray Firth (Beach, 1984; Boote & Gustav, 1987, Harker *et al.*, 1987).

The isochore map for the combined Sgiath and Piper Formations indicates an overall north-south control with the major depocentre trending along the junction between Quadrants 14 and 15. This pattern is attributed to syndepositional movement on north-south "Viking" trend faults (Boldy & Brealey, in press). This combined interval thins eastwards onto the Fladen Ground Spur: this may reflect a combination of depositional thinning and later erosional truncation. In the west, over much of Quadrant 14 and over the Halibut Horst, the Sgiath and Piper Formations are absent. The Halibut Horst is considered likely to have originally been covered by Sgiath and Piper sequences which were subsequently eroded, yielding abundant clastic supply to the Witch Ground Graben during the Late Cimmerian extension, with Piper Sand redeposition and reworking producing the Claymore Member sands of the Kimmeridge Clay Formation.

The effects of Late Cimmerian extensional tectonism are super-imposed upon the north-south "Viking" trend of the Sgiath-Piper isochore pattern. The Sgiath and Piper Formations are eroded from the crestal parts of the tilted fault blocks formed by west-northwest "Witch Ground" trending normal faults (Boldy & Brealey, in press).

The isochore map of the Kimmeridge Clay Formation displays great variability over short distances, clearly showing the change in subsidence and sedimentation patterns, reflecting the strong tectonic control on this syn-rift sequence associated with the opening of the Witch Ground Graben. Despite reaching in excess of 900 m in thickness in the deepest parts of the Graben, the Kimmeridge Clay is absent over a number of positive tectonic features. The Fladen Ground Spur in the eastern part of Quadrant 15 continued as a high area and absence of Kimmeridge Clay here may be a function of both non-deposition and later erosion. A similar scenario is envisaged for the Halibut Horst, which is interpreted to have emerged as a positive block during Kimmeridge Clay times with activation of west-northwest - east-southeast trending faults formed in response to Late Cimmerian rifting. Subsequently, it underwent intense erosion, shedding coarse clastics to form the Claymore Sands, the mineralogical maturity of which suggests that they represent redeposition of Piper Sands.

In summary, then, there are two basic models to consider. The first and simpler envisages a southwards transgression onto the subsiding Central North Sea Dome, pausing while the Piper Sands were deposited in a northwards and westwards prograding delta system sourced from the Dome. This environment was terminated by a combination of transgression in the Kimmeridgian (coeval with graben formation) and rapid subsidence in the Early Volgian. Erosion on the flanks of emergent blocks such as the Halibut Horst and Fladen Ground Spur resulted in localised sand deposition during the Kimmeridgian and Volgian (Boote & Gustav, 1987, Amerada Hess, 1987, Boldy & Brealey, in press).

A second proposal suggests the oldest Humber Group sediments were part of a southeastwards prograding delta sourced from the Fladen Ground Spur. In Piper Sand times the Halibut Horst emerged as a source of arkosic clastics to the southwest, while quartz-arenites were still being deposited from the Fladen Ground Spur in the northeast. Transgression towards the northeast was accompanied by rapid deposition of sands in the west of the area from the active fault scarp of the Halibut Horst. Finally, channelised turbiditic sands were deposited from the NE, with shoreface sands formed against the Halibut Horst during further transgression. in the Late Kimmeridgian/Early Volgian (O'Dricoll *et al.*, in press).

Derivation of Piper Formation sandstones from the Halibut Horst is excluded as a possibility if the Horst is considered not to have been emergent until Kimmeridge Clay times, however (Amerada Hess, 1987; Boldy & Brealey, in press).

The key to resolving the conflict of ideas on this subject seems to depend largely upon the timings of tectonic events that led to the emergence of the stuctural highs that acted as local sources for the Late Oxfordian and Kimmeridgian-Volgian sediments of the area. If the Halibut Horst, controlled by west-northwest - east-southeast orientated ("Witch Ground" trend) faults, did not become emergent as a positive block until early Kimmeridge Clay times then it cannot have acted as a source for the Piper Sandstones of the western part of the area. In discussion of these models, a precise biostratigraphic framework must be employed, and sedimentological, facies and petrological considerations must be taken into account; whilst detailed work may be carried out in a relatively small area, a regional perspective must be maintained. It is important that the anomaly between the two alternative correlations (Fig. 1.4) is clarified because of the significance of the reservoir rocks in the sequence.

2.6 BLOCK 15/21: STRUCTURAL ELEMENTS

The southern flank of the Tartan Ridge extends in an east-west direction across the northernmost part of Block 15/21. The Halibut Horst Spur is the other major positive structural feature, retaining some severely truncated Jurassic section; the Halibut Horst itself is a very shallow feature with little or no Mesozoic section preserved (Fig. 1.7).

Two grabens traverse Block 15/21, reflecting the two different fault trends recognised in the area. One graben separates the Halibut Horst from an area of intermediate structural relief in the southernmost part of Block 15/21, the Ivanhoe/Rob Roy Platform (Boldy & Brealey, in press) where the Ivanhoe and Rob Roy Fields are located. This is bounded by northeasterly trending "Viking" faults and is termed the Theta Graben (Boldy & Brealey, in press). Although most clearly defined in the southern part, it continues at depth to the northeast where it intersects a graben traversing the northern half of Block 15/21, defined by east-west and northwest-southeast faults of the "Witch Ground" trend. This, North Halibut Graben, separates the Tartan Ridge to the north, from the Halibut Horst to the south.

2.7 TRAP STYLES - IVANHOE AND ROB ROY FIELDS (BLOCK 15/21A)

The most important traps in the Outer Moray Firth are structurally controlled, predominantly tilted, fault block structures formed by extensional tectonism. The Ivanhoe and Rob Roy Fields are both typical of rotated and tilted fault blocks, with upthrown fault closure traps (Amerada Hess, 1987). Erosion of the Piper reservoir section on the crest of the Rob Roy structure is considered to have occurred: this is common in tilted fault block traps of the area (Piper, Tartan, Claymore, Galley) as well as in the Brent Province. Top seal and side seal, across the boundary faults, are provided by the Kimmeridge Clay Formation, except locally along the bounding fault of the Rob Roy Field, where calcareous claystones of the Lower Cretaceous Cromer Knoll Group provide lateral seal against reservoir sands (Fig. 3.19).

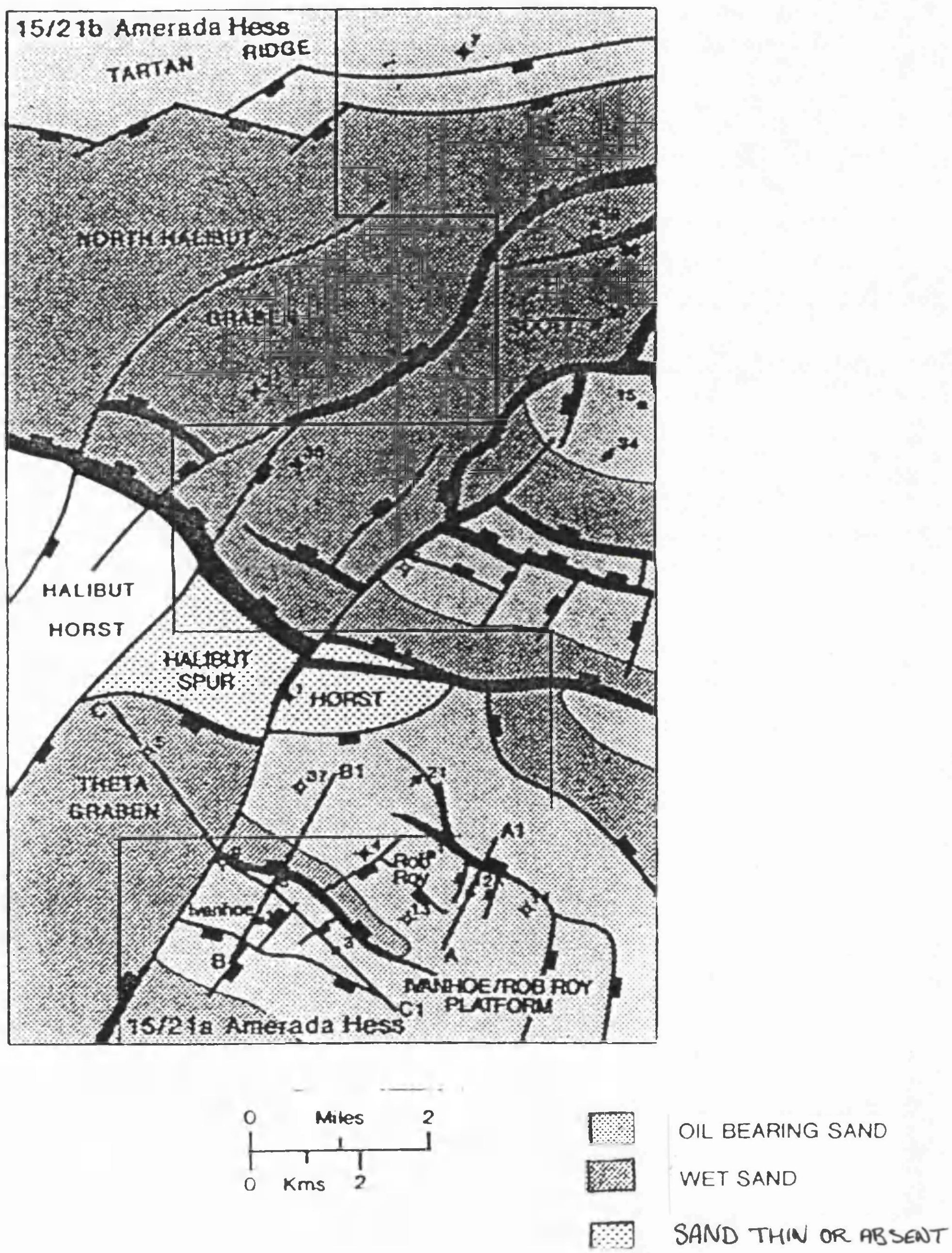


Fig. 1.7. Block 15/21: Structural elements. From Boldy & Brealey (in press).

3. METHODS AND TECHNIQUES.

3.1 AMMONITE PRESERVATION AND PREPARATION.

North Sea Specimens.

Cored shale sequences from six wells in Block 15/21 and one in 15/22 were examined for macrofossils, and ammonites collected for biostratigraphical determination. Core from four wells (15/21a-4, 11, 12a and 15/22-5) was examined by Dr. Nicol Morton of Birkbeck College as a precursor to the present study. Ammonites were collected from cores of 15/21a-15 and 15/21a-25 at the Kestrel holding house in London and from 15/21a-29 at Dyse, Aberdeen, by the author.

Several of the ammonite specimens recovered have been preserved uncrushed in nodules which were lithified by early diagenesis before compaction, but the large majority were crushed during compaction. However, ventral as well as lateral views are available as a large proportion of the specimens were buried at a high angle to the bedding.

State of preservation varies between wells - length of time of exposure of the core to oxidation wields influence here: it appears that cores of these dark pyritic and organic shales deteriorate rapidly. 15/21a-25 yielded several specimens with the aragonitic shell preserved.

Each sample is labelled with well number and depth. Laboratory preparation as necessary was carried out using fine chisel or scalpel for flaking matrix. Dr. Morton carried out some more detailed work using a vibrotool or air abrasive. Less well preserved specimens have been sprayed with Letraset 103 Letracote Matt to give a protective laquer coating.

Onshore specimens.

As all specimens were collected from shale sequences, preservation is almost universally poor, with the vast majority of specimens being crushed. At South Ferriby there are many uncrushed specimens, including macroconchs of *Pictonia* and *Rasenia*, yet these prove difficult to extract from the fissile shale - in most cases only the body-chamber is uncrushed and these usually fragment when disturbed. Uncrushed nuclei are numerous, but of little value in identification amongst this group of ammonites. The specimens are labelled with the date and a number. Laboratory preparation involved the use of a scalpel for flaking away the matrix, and coating specimens in more crumbly shale with clear polyurethane varnish.

At Eathie, Cromarty, the vast majority of specimens were collected from a hard calcified bed (Waterston's 1951 Second Limestone), and although crushed to varying degrees, are extremely well preserved. Other Eathie specimens came from saturated, fissile shales on the foreshore, and although often they have aragonite preserved, they are extremely fragile.

The specimens collected along the Brora-Helmsdale strip of Kimmeridgian exposure are all crushed and come mainly from extremely fissile shales. Ammonites occurred more frequently in the softer, more crumbly beds; the siltier, harder beds which split along the bedding planes were not so productive. Preservation was markedly poorer on the West Garty section, with the shale being blockier and more silty than in the lower parts of the sequence, and the scarce ammonites were in extremely poor condition. The specimens from northeast Scotland were again labelled with the date and a number, and coated with a clear polyurethane varnish for protection and strengthening.

3.2 PALYNOLOGICAL PREPARATION.

In addition to the palynological preparations obtained from GeoStrat Ltd., samples were prepared for palynological investigation from the South Ferriby section, and from cores 1 and 2 of the 15/21a-25 well. Sample size used was 10 gms.

The samples were initially washed to remove any surface contaminants, for example drilling muds, and broken into small fragments which were put into a plastic beaker and sprinkled with water to prevent dust reacting explosively with the acids. First the sample was covered with HCl to remove carbonate material, and left for 24 hours with occasional agitation. At the end of this period, the acid was decanted into a bucket containing quicklime solution, removing as much of the reactant as possible.

The silicates were then removed using HF, again for 24 hours with occasional agitation of the plastic beaker. After this time, the acid was decanted into the quicklime solution and water added to the residue in the beaker, which now had a muddy consistency. This indicates that the kerogen is ready for post-acid treatment.

The residue was first sieved through a 10 μ mesh, being careful that the solution was not too acidic, and the residue was placed into a small bottle.

Two sets of slides were required from each sample, for palynofacies analysis and for biostratigraphic analysis. For the former, no further treatment was necessary; for the latter the sample was swirled in a 7" petri dish to remove the generally heavier and larger woody material, leaving a clean residue. No staining was undertaken.

A few drops of deflocculant were added to each residue (Fairy Liquid detergent), and residue placed on the cover slips with a pipette. The cover slips were mounted on to the slides using Canada Balsalm or Norland Optical Adhesive. The latter mounting medium was found to be preferable, because of ease of use and quality of results.

3.3 FIELDWORK DETAILS.

Field excursions were carried out at South Ferriby in May, 1988, and June, 1990; in Northeast Scotland in July, 1989; and on the Yorkshire and Dorset coasts in summer and autumn 1988.

PART 2 - THE STRATIGRAPHIC AND PALAEONTOLOGICAL DATABASE

4. SECTION AND LOCALITY DATA.

4.1 OFFSHORE.

Core material from 10 wells from Blocks 15/21a and 15/22 in the Outer Moray Firth was examined in order to resolve the biostratigraphic anomaly between dinoflagellate cysts and ammonites. Their locations are shown on Fig. 2.1, and details of the lithological successions are described in the introduction (p. 23). Table 1 is to show recovery of flora and fauna, and sample type:-

Well	Ammonites	Dinocysts	Cutting	Core
15/22-5	+	+	+	+
15/21-4	+			+
15/21-11	+	+	+	+
15/21-12a	+	+	+	+
15/21-15	+			+
15/21-16		+	+	+
15/21-18		+	+	+
15/21-25	+	+	+	+
15/21-29	+			+
15/21-33		+	+	+

Table 1. Core material, Blocks 15/21, 15/22.

4.2 ONSHORE

South Humberside.

Middlegate Quarry at South Ferriby (Ordnance Survey 1:50,000 Second Series Sheet 112 [TA 991 204] - Fig. 2.2) is worked by the Rugby Portland Cement Company. The Jurassic part of the succession underlying the Cretaceous Carstone and chalks, consists of Oxfordian and Kimmeridgian deposits - this section shows one of the thickest, most complete and fossiliferous successions through the Oxfordian/Kimmeridgian boundary in Northwest Europe. The section is mentioned by Cox (in Smart & Wood, 1974, p. 592), and is briefly described by Ahmed (1987) and Birkelund & Callomon, 1985, P. 17), where Callomon described a thicker succession with about 20 m of Ampthill Clay, from a previous exposure.

The Ampthill Clay, of late Oxfordian age, consists of approximately 9 m of dark well-bedded clays with sporadic layers of concretions and nodules. The Kimmeridge Clay consists of about 8 m of grey clays, often calcareous, with silty bands and a layer of large cementstone concretions. Increased concentrations of phosphate are seen occasionally, and towards the top the clays become increasingly fissile.

The section described in this work is a composite taken from faces on the south side

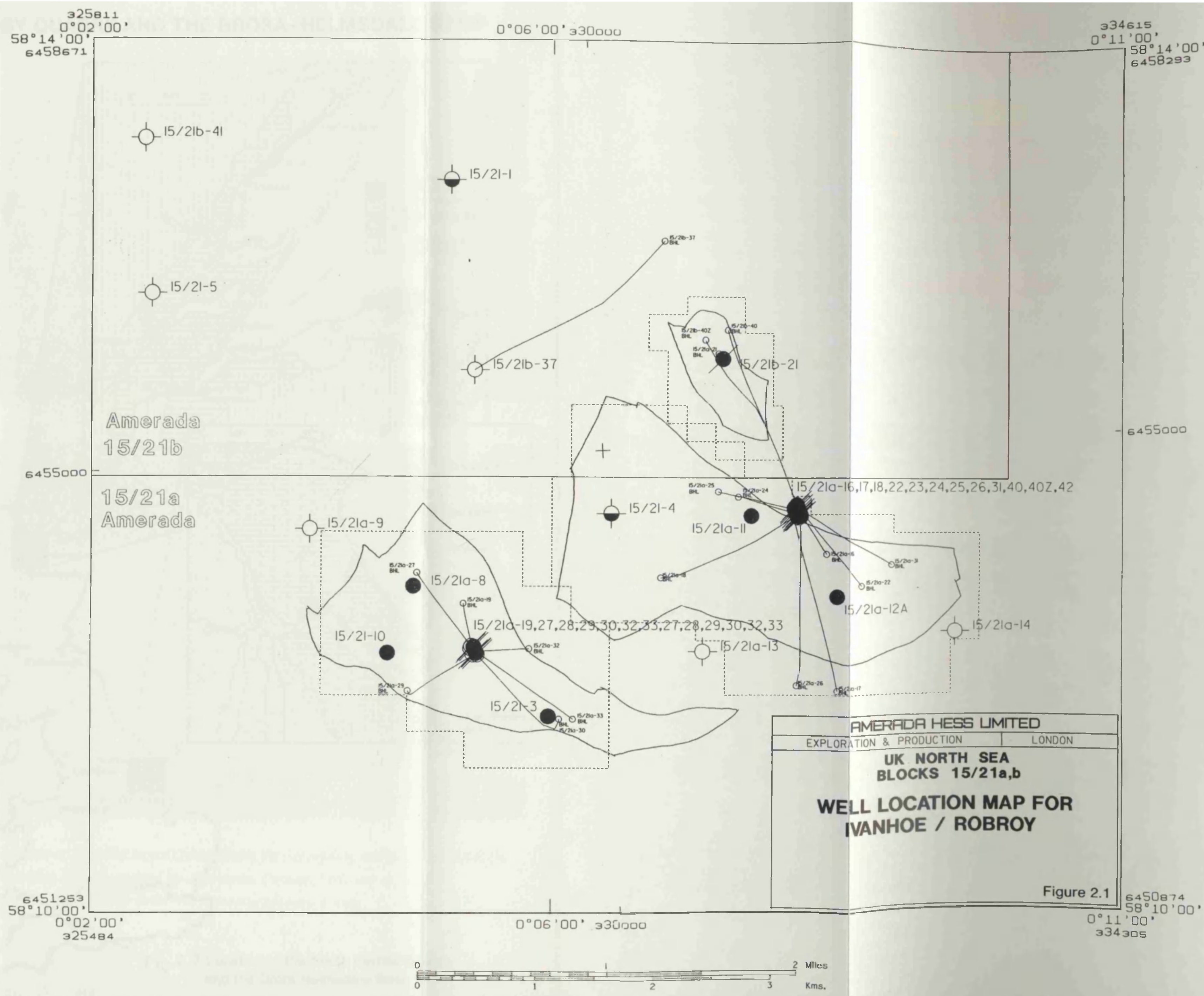

325811
0°02'00'
58°14'00'
6458671
0°06'00' 330000
334615
0°11'00'
58°14'00'
6458293
15/21b-41
15/21-1
15/21-5
15/21b-37
15/21b-21
6455000
Amerada
15/21b
15/21a
Amerada
15/21a-9
15/21-4
15/21a-11
15/21a-16,17,18,22,23,24,25,26,31,40,40Z,42
15/21a-8
15/21-10
15/21a-19,27,28,29,30,32,33,27,28,29,30,32,33
15/21a-12A
15/21a-13
15/21a-14
15/21-3
AMERADA HESS LIMITED
EXPLORATION & PRODUCTION
LONDON
UK NORTH SEA
BLOCKS 15/21a,b
WELL LOCATION MAP FOR
IVANHOE / ROBROY
6451253
58°10'00'
0°02'00'
325484
0°06'00' 330000
6450874
58°10'00'
0°11'00'
334305
0
1
2 Miles
0
1
2
3
Kms.

Figure 2.1

FERRIBY QUARRY AND THE BRORA–HELMSDALE STRIP

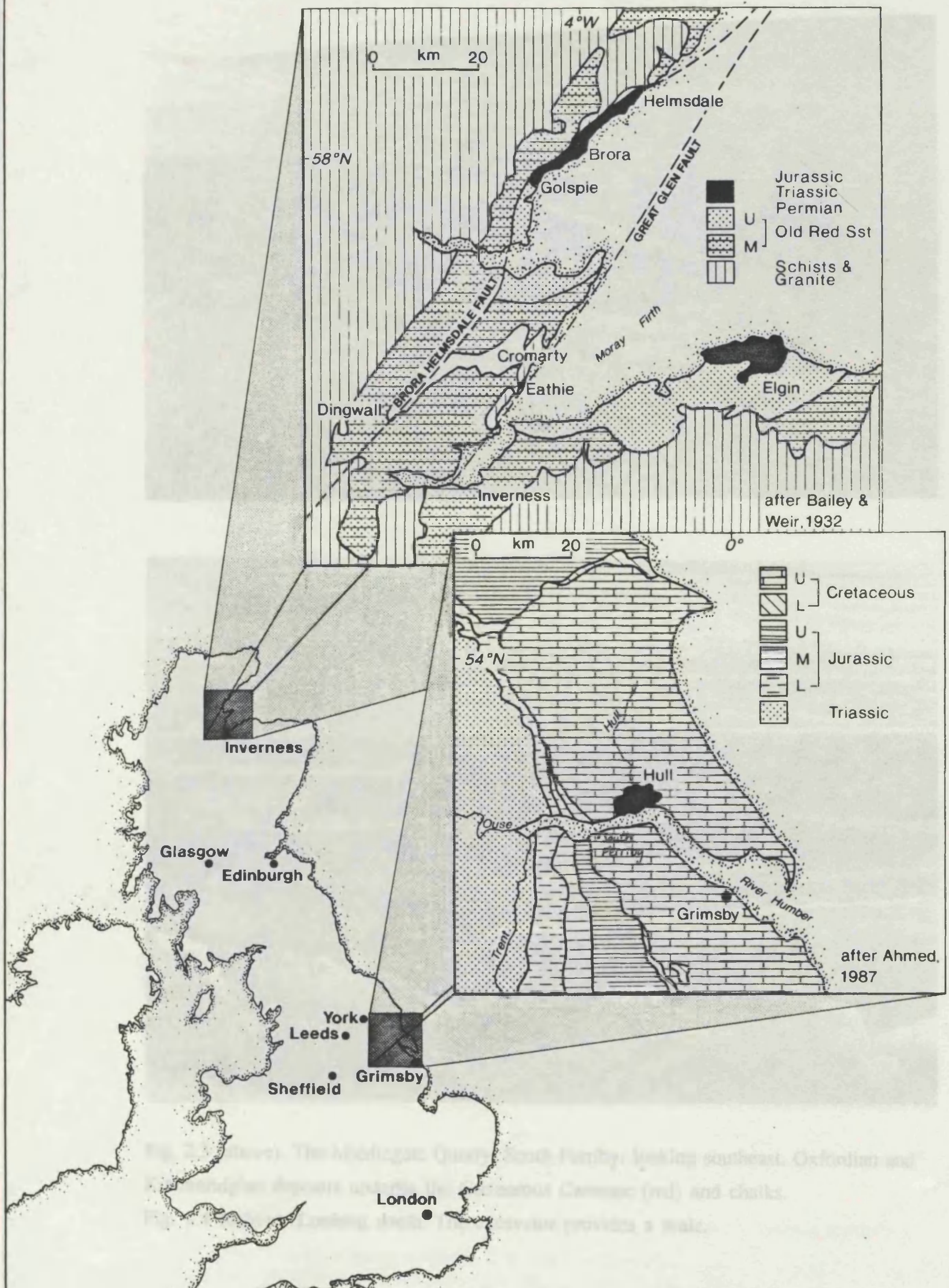


Fig. 2.2 Location of the South Ferriby Quarry,
and the Brora Helmsdale Strip

Fig. 2.3 (above). The Middlegate Quarry, South Ferriby: looking southeast. Oxfordian and Kimmeridgian deposits underlie the Cretaceous Carstone (red) and chalks.

Fig. 2.4 (below). Looking south. The excavator provides a scale.

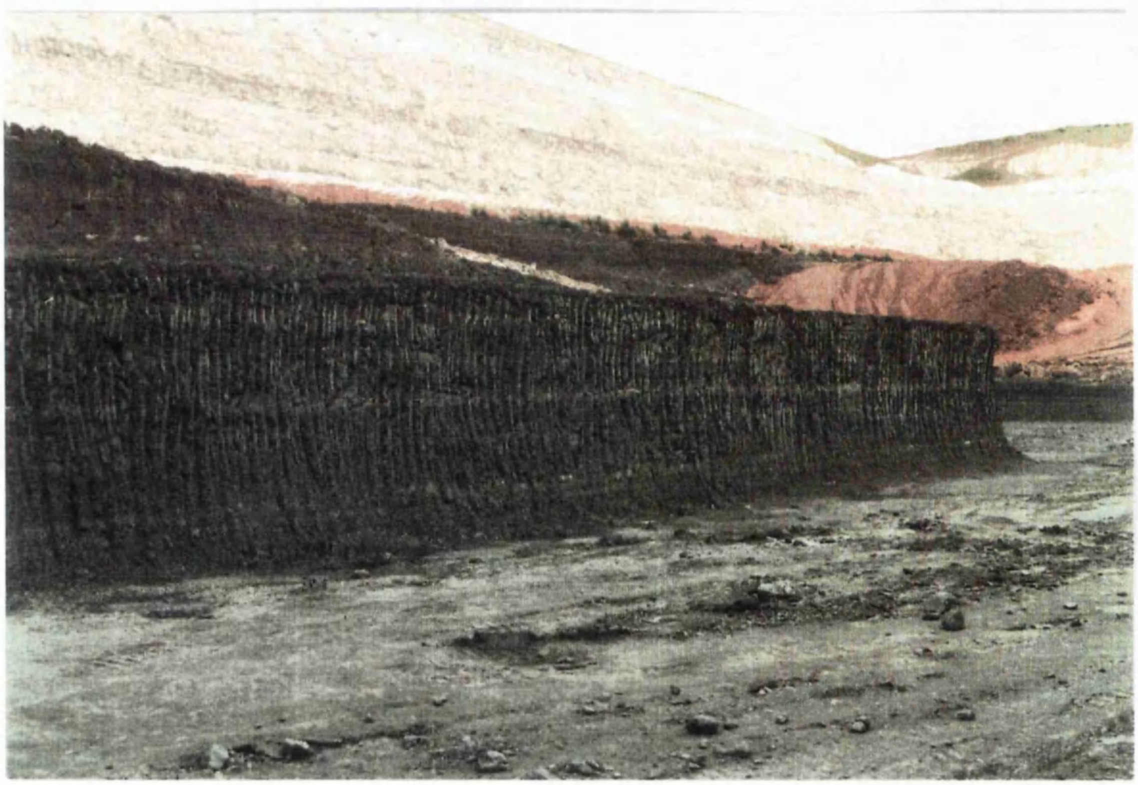


Fig. 2.5 (above). The Cymodoce and Baylei Zones, looking south. The author's hammer points at Bed 17; Louise Barron stands below on Bed 13.

Fig. 2.6 (below). Foreground face, Upper Oxfordian Beds 1-10 (pars.), looking southwest. The distinctive marker bands of Beds 3, 5 and 7 are visible.

of the quarry (field visit June, 1990) and a now buried face in the western end of the quarry (visited in May, 1988). The boundary between the Hunstanton Formation (Red Chalk) and underlying Carstone is where (in the southern and western sides of the quarry) an access road has been constructed, the Hunstanton Formation having been cut back to leave a terrace on (approximately) the top of the Carstone. The Carstone here has a laterally variable basal pebble bed:- in some places the matrix is a coarse bright ochre sand, in others it is more clayey and pebbles are scarce.

Description of Section (Fig. 2.7)

Bed no.			metres
	Carstone		
	-----unconformity-----		
Kimmeridge Clay			
20	Grey clay. Not readily divided; following provisional section made:		3.60
	(basal Carstone pebbles)		
	grey clay	0.80	
	reddish-weathering paler clay	1.15	
	grey clay	0.35	
	ammonite plaster - all horizontal, up to 15 cm diameter (2.3 m below top) - *Rasenia*		
	grey clay	0.80	
	ammonite plaster, as above (3.1 m below top)		
	grey clay	[0.50?]	
	(silty bed beneath hidden where this was measured)		
19	Silty, reddish-brown weathering hard band, the most prominent brown marker. Fresh surface grey. Contains uncrushed bivalves. In places appears blocky, sometimes almost like a nodule band.		0.10
18	Clay - dark above grading down to a paler bottom 0.2 m. In places siltier and browner. Many large horizontal crushed *Pictonia* and pyritised nuclei.		0.70
17	Thin brownish-weathering, slightly silty (?) bed, not indurated		0.03
16	Clay - dark above grading down to paler, harder more calcareous clay with *Prorasenia*, *Amoeboceras bauhini*, and *Ostrea*.		1.05
15	Brown-weathering, slightly silty (?) bed, slightly harder than		0.05

DIAGRAMMATIC REPRESENTATION OF THE SOUTH FERRIBY SECTION

FM.	BED.	LITHOLOGY	REMARKS AND FAUNA	ZONE
KIMMERIDGIAN – KIMMERIDGE CLAY	20		Grey clay. *Amoeboceras cricki* *Rasenia* cf. *evoluta* Reddish - weathering clay. Grey clay. Ammonite plaster *Rasenia* sp. indet. Grey clay. Ammonite plaster *Rasenia* sp.indet. Grey clay.	CYMODOCE
	19		Red – brown weathering hard band.	
	18		Clay, dark above grading to paler below. *Prorasenia* aff. *triplicata*, *Pictonia* cf. *baylei*	BAYLEI
	17			
	16		Clay, dark above grading down to paler, harder, more calcareous clay. *Prorasenia*, *Amoeboceras bauhini*	
	15			
	14		Clay. *Pictonia* cf. *densicostata* *Prorasenia* cf. *bowerbanki* *Amoeboceras cricki.* *Amoeboceras bauhini.*	
	13		Pale clay with concretions up to 1m long.	
	12		Clay.	
	11		Scattered, rotton nodules	
OXFORDIAN – AMPTHILL CLAY	10		Clay. *Prorasenia bowerbanki* *Ringsteadia* cf. *evoluta* Band of circular nodules.	PSEUDOCORDATA
	9		Scattered circular nodules	
	8		Clay,darker in lower half. *Ringsteadia* sp. indet.	
	7		Pale clay, concretions in lower part.	
	6		Dark clay	
	5		Clay, double pale band with dark band between.	
	4		Dark clay.	
	3		Clay, double pale band with dark band between.	
	2		Dark clay.	
	1			

Figure 2.7

surrounding clays.

14 Clay- highly fossiliferous. Load structures related to occasional sedimentation of brown silty mud. 2.00

13 Paler-weathering clay band with irregularly developed concretions up to 1 m long. The most prominent marker bed. 0.20

12 Clay- dark, calcareous and highly fossiliferous. Fossils similar in number and preservation (crushed) to bed 14, though here there are occasional uncrushed body-chambers, infrequently filled with shelly limestone. 0.20

11 Band of scattered, pale brown (phosphatic?), rotten nodules, usually small (2-3 cm) but some larger platy examples (to 15x5 cm) c.0.20

Ampthill Clay

10 Clay (measured from one bench down to another, so thickness is approximate). Ammonites, gastropods, bivalves; crushed or partially pyritised. Some browner, silty (?) layers. c.3.50
Band of scattered circular nodules (potato stones), diameter c. 15 cm at base.

9 Moderately dark clay, in places quite pyritic, fossils may be partially pyritised, and small (mm scale) rotten pyritic nodules. 0.70
Band of scattered circular nodules (potato stones), diameter c. 15 cm at base.

8 Clay, possibly darker in lower half. 1.10

---sharp dark/pale contact---

7 Pale, slightly khaki-weathering clay with flattish small concretions (c. 30 x 5 cm max.) lying in topmost part. Forms a very distinctive bed, which grades down into c.0.20

6 Dark clay, in places silty (?), traces of ammonite nuclei frequent as "rust stains" (from oxidation of pyrite?). 0.50

5 Clays: double pale band with thin (c. 10 cm) dark clay between. c.0.45

4	Dark clay	0.85
3	Clays: double pale band with thin dark clay between: divisible into - pale clay* 0.25 dark clay 0.10 pale clay 0.20 *with very scattered concretions (c. 30 cm long) but only 3 along one face, none along others.	0.55
2	Dark clay.	1.00
1	Large septarian concretions forming floor of quarry.	

(Section as described 26-27th June, 1990, with Dr. P. F. Rawson)

Moray Firth.

Brora-Helmsdale strip.

Isolated exposures of Jurassic rocks occur on the eastern coast of Sutherland and Ross. The largest of these is a broken succession from Lias to Kimmeridge Clay in the Brora-Helmsdale region (Fig. 2.8). The Jurassic of the Brora outlier represents the exposed western margin of a large sedimentary basin extending eastwards beneath the Moray Firth (Lam & Porter, 1977). The coastal sections are the only portions of the succession not covered by drift. They have been described in detail in the Geological Survey Memoir (Lee, 1925) and by Bailey & Weir (1932); and more recently by Linsley (1972), Sykes (1975b), Brookfield (1976), MacDonald (1985) and Tyson (1985, 1989).

The section studied (Kintradwell-West Garty) is all Kimmeridgian in age, and therefore time-equivalent to the Piper Formation and the Kimmeridge Clay Formation in Blocks 15/21 and 15/22. The succession consists largely of shales with subordinate (<25%) proximal, turbiditic sandstones and the clast-rich debris flows known as the area's "boulder beds" (Tyson, 1989). The shales are typically dark grey to black and organic-rich, and were deposited below wave base in a dysaerobic to anoxic basinal environment developed on the downthrown side of an active submarine fault scarp (Pickering, 1984; Tyson, 1989). In the western part of the Lothbeg area, the type Allt na Cuile Sandstone is a fine- to very-fine-grained yellow friable sandstone with intercalated massive horizons, pebbly lenses and breccias (Tyson, 1989).

The sections were chosen for comparison because of their proximity to the offshore area and the length of uninterrupted sequence of shale in successively younger Kimmeridgian sediments, heading in a north-easterly direction along the coast from

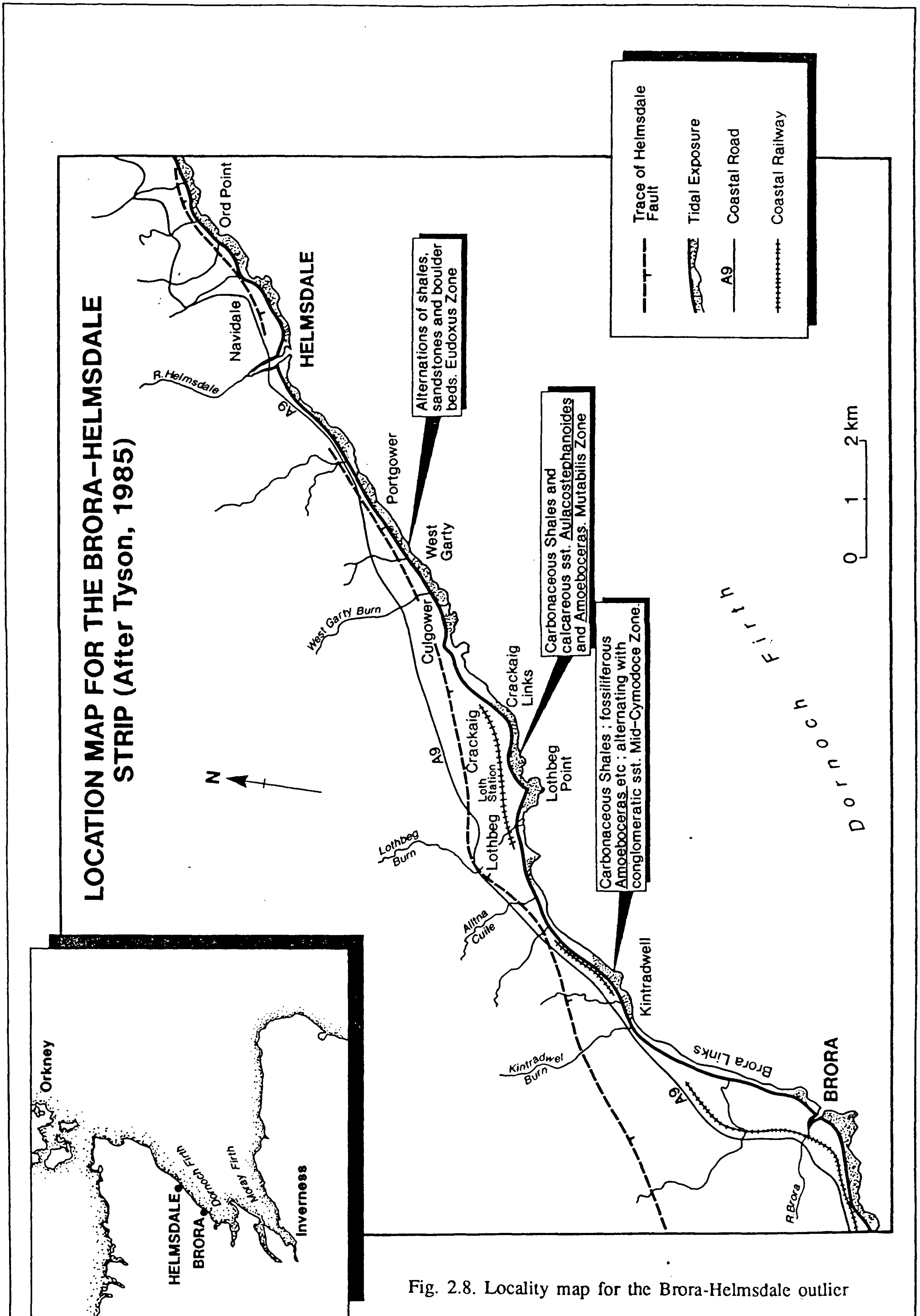


Fig. 2.8. Locality map for the Brora-Helmsdale outlier

Kintradwell to West Garty. The oldest Kimmeridgian encountered is of *cymodoce*-Zone age at Kintradwell; at West Garty *eudoxus*-Zone aged sediments are reached. The grid references refer to Ordnance Survey 1:25,000 series Maps NC 80/90 and NC 81/91.

Kintradwell. NC 80/90 926074 - Cymodoce Zone.

Most westerly Kimmeridgian exposure (Section A2 in Tyson, 1985). Comprised mainly of dark grey to black, organic-rich carbonaceous shales, with substantial numbers of silty laminae and finely-grained sandstone stringers (<1 cm thick). Occasional harder calciferous sandy bands protect the shales below them from erosion. The section is largely sand-covered; dip is to the North. The fauna includes ammonites (more frequent in the softer, more crumbly beds with the harder, siltier beds not so productive), belemnite guards, bivalves and occasional oysters.

Lothbeg River. NC 80/90 954098 - Mutabilis Zone.

Close to the type section of the "Loth River Shales" (NC 952099; see Arkell & Callomon, 1963, p. 242 and Brookfield, 1976, p. 182; Section B15 in Tyson, 1989). Shales highly carbonaceous with occasional fine grained sand beds (~2 cm thick) which become more frequent towards more major sandstone beds. Some totally decalcified shales leave only the impressions of fossils: *Amoebites* is prolific at some levels in darker, less fissile shales, and *Inoceramus* and *Buchia* are also represented.

Crackaig Links. NC 80/90 961095 - Mutabilis Zone. (Fig. 2.9)

Thick shale sequence (30.5 m) just north-east of Lothbeg Point (Section B22 in Tyson, 1989) between high-water-mark and low-water-mark. The beds dip at 30 NE. The shales are dark grey to black, carbonaceous and fossiliferous with ammonites, fish remains, bivalves and plant remains. At the base is a 1.5 m sandstone. This is a thinly-bedded (1 cm), clean, calcite-cemented, fine- to medium-grained, pale grey sand, often quite flaggy with occasional thin shale interbeds. Above this, sandstone occurs only in thin beds, varying in thickness from 1-10 cm across the strike. These often yield ammonite imprints on their occasionally erosive bases, and may also show carbonaceous laminae. The thin sands amount to no more than 4% of the sequence (Tyson, 1985). The shales are generally full of crushed and fragile ammonites. Six metres above the base of the section is a clay marker band, distinctly waxy and pale grey. One metre above this is a nodule band with fairly sparse, cemented shale nodules up to 10 cm long (none of which yielded ammonites when opened). Up-sequence from here ammonites become notably less frequent. The shales become softer and friable and preservation is very poor; at some levels there is abundant plant material, and occasional lenticular calcite cemented shales weathering out. In the last ~10 m to the low-water-mark the shales proved barren except for plant material and infrequent fish remains.

Fig. 2.9. Foreshore exposure at Crackaig Links, looking southwest.

At NC 80/90 959095, just south-east of Lothbeg Point, the exposed shales are extremely fissile, with very poorly preserved fossils, usually just faint impressions. Sand is abundant forming interbedded laminae, and the sand content varies, in places being more cemented and blocky.

West Garty. NC 81/91 993119 - Mutabilis-Eudoxus Zone.

Section on the north-east limb of the Culgower syncline (the E Shale, sections E1 and E2 in Tyson, 1989), dip 30 SE. The base of section E1 is 150 m northeast of the mouth of Westgarty Burn, in a variably cemented sandstone (outcrop L) which is overlain by a shelly boulder bed and sands. The remainder comprises shales with a lenticular boulder bed (outcrop J), and at the top of E1 is a clast-supported boulder bed (outcrop G), a composite unit of two or more overlapping boulder beds. Section E2 carries on directly above outcrop G; it comprises mainly shale with common thin (<1 cm thick) sandstone stringers, with a few calcite-cemented sandstones. Outcrop D at the top of E2 is a complex of sandstones and boulder beds with shales. The clasts are up to 75% Old Red Sandstone (plus siltstones and limestones); the shales include lenticular and boulder sandstones.

Eathie, Cromarty. (Fig. 2.10)

There is only one other exposure of Kimmeridgian rocks in the Moray Firth area, 30 miles southwest of Brora at Eathie Haven on the eastern shore of Black Isle, 3 miles south of Cromarty. Black shales and limestones are exposed in a narrow strip, about one mile long, which is covered by water other than at low tide. The succession was best described by Waterston (1951). The oldest Kimmeridgian occurs in the southernmost part of the exposure bounded to the west by the fault junction against the Moine Gneiss. After green-grey calcareous mudstones interbedded with limestones are about 2 m of olive-black shale, followed by about 10 m of grey shaley mudstones (the "Astarte Muds" of Waterston, 1951). The remaining 40 m or so consist of olive-black shales and oil-shales, which are richly fossiliferous, many bedding planes being covered with flattened ammonite shells. Waterston (1951) describes 4 marker bands:- a shaley bed 60 cm thick ~16 m above the "Astarte Muds" crowded with *Meleagrinella;* a First Limestone 30 cm thick 4 m above this, light olive-grey weathering to yellow brown; a second *Meleagrinella* band 45 cm thick 5 m above this; and a Second Limestone, ~16 m above the first, which is bedded and arenaceous, dark grey weathering to light olive-grey. Both limestones contain the remains of species that occur in the surrounding shales. On the date of the field visit (25th July, 1989), specimens were collected from the Second Limestone and surrounding shales, the lower part of the section being under water.

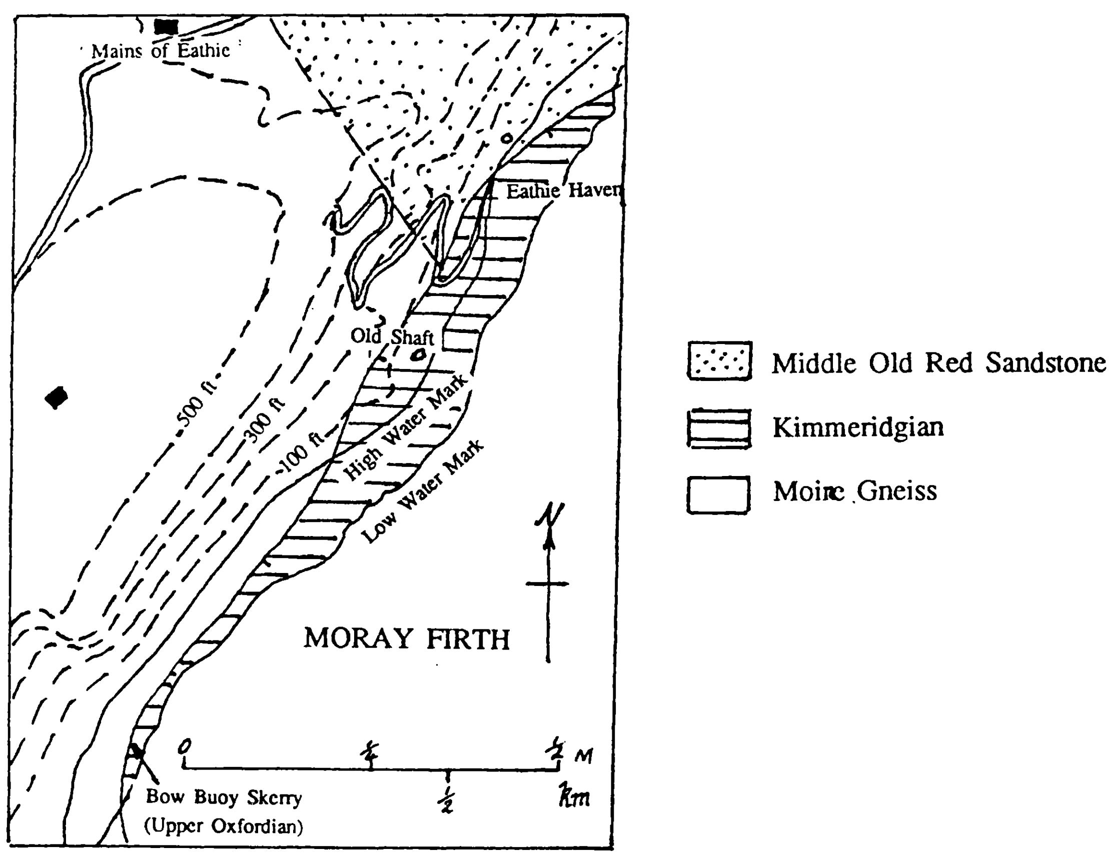


Fig. 2.10. Locality map for the Eathie Kimmeridgian exposure (after Waterston, 1951).

5. SYSTEMATIC DISCUSSION OF
AMMONOIDEA

In the synonomy of species, only the first description, major revisions and subsequent discussions of Boreal or sub-Boreal biostratigraphic importance are listed. In type material specimen numbers; BM = The Natural History Museum (London), MGUH = The Geological Museum of the University of Copenhagen.

5.1 Superfamily: **STEPHANOCERATACEAE** Neumayr, 1875

Family: **CARDIOCERATIDAE** Siemiradzki, 1891

Subfamily: **CARDIOCERATINAE** Siemiradzki, 1891

Genus *Amoeboceras* Hyatt, 1900

Type species. *Ammonites alternans* v. Buch, 1831

Subgenus *Amoebites* Buckman, 1925

Type species. *A. akanthophorus* [=*A. kitchini* (Salfeld)]

Differs from *Amoeboceras* s.s. (small, strongly-ribbed microconchs) and *A. (Prionodoceras)* (large macroconchs becoming smooth on the adult body-chamber), which characterise the Upper Oxfordian, by not developing the mid-lateral tubercles on the primary ribs, instead developing stronger secondary ribbing or spines on angular ventro-lateral shoulders. The earliest development of this characteristic is seen in *A. bauhini*, which possesses a smooth band between long primaries and short secondaries; the extreme is seen in *A. kitchini*, characterised by massive ventro-lateral spines or clavi, which may develop by the looping of two or more secondary ribs.

Amoeboceras (Amoebites) bauhini (Oppel)

Plate 4 Figs. 1-4

1858 *Ammonites alternans* Quenstedt, p. 595, pl. 74, fig. 6[m] (holotype)

1863 *Ammonites bauhini* Oppel, p. 210

1979 *Amoeboceras bauhini* (Oppel); Sykes & Callomon, p. 889, pl. 121, figs. 1-

5

1985 *Amoeboceras (Amoebites) bauhini* (Oppel); Birkelund & Callomon, p. 15-17, pl. 9, figs. 8-13

Material: Numerous specimens; beds 14 and 16 South Ferriby; one each from Wells 15/21a-15, 15/21a-29.

Holotype. Specimen figured by Quenstedt (1858) from Hundsruck, Swabia, White Jura β.

Diagnosis. Small species, holotype diameter 26mm, characterised by sharp primaries curving backwards to a lateral tubercle a little over halfway up the whorl-flank, a prominent spiral smooth band above these, and then short, dense tuberculate secondaries on the ventro-lateral shoulder. Quadrate and depressed whorl-section; keel sharply crenulated and barely raised above the venter.

Remarks: The core material agrees well with the holotype. The South Ferriby specimens are of a more finely ribbed variety, and the secondaries may meet the keel rather than there being smooth sulci along its sides.

Range: As discussed in the biostratigraphic framework (p. 99), the Bauhini Subzone, has been redefined as being largely if not exactly equivalent to the Baylei Zone, and entirely Kimmeridgian in age.

Amoeboceras (Amoebites) cf. ***subkitchini*** Spath

Plate 4 Fig. 5

cf. 1935 *Amoeboceras (Amoebites) subkitchini* Spath. p. 30, pl. 1, fig. 3 a, b (Holotype)

cf. 1985 *Amoeboceras (Amoebites) subkitchini* Spath; Birkelund & Callomon, p. 19, pl. 2, figs. 1-7, pl. 3, figs. 1-11.

Material: 5 specimens; 2 from well 15/21a-4, 2 from 15/21a-12, 1 from 15/21a-25.

Holotype of A. subkitchini: Specimen figured by Spath (1935), MGUH 8412, from Milne Land, East Greenland.

Diagnosis. Small forms (largest diameter seen 15 mm), with strong crenulate keel. Strong, sharp, close primaries to just over half whorl-height. Secondaries strongly rursiradiate at first, forming shallow ventro-lateral clavi.

Remarks. According to Birkelund & Callomon (1985), *A. subkitchini* is the senior synonym for a single highly variable species including *A. aldingeri, A. irregulare* and *A. prorsum* (all first described by Spath,1935, from the same horizon). *A.*

subkitchini marks the most common forms, with the most finely ribbed inner whorls, and *A. prorsum* the most coarsely ribbed. Microconch specimens from the same beds are close to the holotype of *A. rasenense*, from Market Rasen, Lincolnshire but are more finely ribbed. The closely related, later group of *A. kitchini* [M] is smaller with coarser ribbing, and heavier and more strongly differentiated nodes and clavi and deeper ventral sulci than *A. subkitchini [M]*. If *A. rasenense* is taken to be the microconch of *A. kitchini* (see below), the microconchs seem to follow the same trend toward coarser ribbing from the earlier finely-ribbed *A. subkitchini* [m].

Range: *A. subkitchini* and *A.* sp. aff. *kitchini* occur in faunas characterised by *Rasenia inconstans* and *R. cymodoce* (belonging to the lower part of the Cymodoce Zone) in Greenland (Callomon & Birkelund, 1980).

Amoeboceras (Amoebites) kitchini (Salfeld)

Plate 4 Figs. 6, 7

1913 *Cardioceras kitchini* Salfeld, p. 423 (Holotype description)

1915 *Cardioceras kitchini* Salfeld, pl. XX, fig. 16 (illustration)

1925 *Amoeboceras (Amoebites) akanthophorus* Buckman, pl. DL

1935 *Amoeboceras (Amoebites) kitchini* (Salfeld); Spath, p. 30, pl. 1, figs. 9 a, b

1951 *Amoeboceras (Amoebites) kitchini* (Salfeld); Waterston, p. 42, pl. ii, figs.4 a, b.

1976 *Amoeboceras (Amoebites) akanthophorus* (S.S.Buckman); Sykes & Surlyk, fig. 7B

Material: 9 specimens; 4 plus 1 *A.* cf. *kitchini* from Eathie, 2 plus 1 *A.* cf. *kitchini* from Crackaig Links, 1 *A.* cf. *kitchini* from well 15/21a-29.

Holotype: Figured by Salfeld, 1915, pl. XX, fig. 16.

Diagnosis: Moderately evolute forms with strongly crenulate keel, strong, coarse primaries to ventro-lateral shoulder where massive spines or clavi develop, often by looping of two or more secondaries.

Description: The maximum diameter is c. 50 mm; on this specimen the umbilical diameter is 33% and whorl height is 36%; though the specimen is slightly crushed and distorted, the others show similar ratios. The ribbing of the inner whorls is rather coarse and sharp; poor preservation prevents more detailed examination. On the outer whorls of the two most completely preserved specimens (both from Eathie) the ribs are slightly rursiradiate at the umbilical seam becoming rectiradiate on the flanks. There are 33 and 35 primaries on the outer whorls, becoming coarser with increasing diameter. The ribs become coarser away from the umbilical seam to just over mid-way up the flanks, and then fade towards the venter to varying degrees. In one of the Crackaig Links specimens they fade completely at about three-quarters whorl height; others just show a slight decline before reaching the ventro-lateral shoulder. The ventro-lateral tubercles are well developed becoming stronger and more distantly spaced with increasing diameter. The ratio of clavi to primaries varies from 1:2 to 1:5. The venter shows a completely differentiated keel which is coarsely serrated and flanked by sulci at the sides.

Remarks: The only specimen from a cored shale sequence is a venter only, from which the tips of the clavi are broken; its width (22 mm) would suggest a diameter at the upper limits recorded for this species (c. 80 mm - Waterston, 1951). There is too little of the shell preserved to afford certain identification, but what there is fits best with *A. kitchini*. Of the onshore specimens, one from Eathie and one from Crackaig Links are too poorly preserved, with most damage to the outer whorl, for unequivocal identification.

Range: At Eathie, all specimens came from one hard band, Waterston's (1951) Second Limestone, yielding *Rasenia (Rasenioides) askeptus*, indicative of the lower Mutabilis Zone. The Crackaig Links specimens occur together with *Amoebites beaugrandi* and *Aulacostephanoides mutabilis*, characterising the mid-Mutabilis Zone.

At Eathie the range of *A. kitchini* is known to extend from the *R. evoluta* horizon (Birkelund *et al.*, 1978) in the upper Cymodoce Zone to the lower Mutabilis Zone, associated with *A. rasenense*; at Market Rasen it occurs in the Cymodoce Zone with *A. rasenense*; and Arkell & Callomon (1963) figured a specimen from the Mutabilis Zone from the drift of Lincolnshire. Sykes & Surlyk (1976) cite it as ranging from the Cymodoce Zone to the Mutabilis Zone.

The specimen of *A.* cf. *kitchini* from 15/21a-29 seems by association with *R. evoluta*, to belong to the upper Cymodoce Zone.

Amoeboceras (Amoebites) rasenense Spath

Plate 4 Figs. 8, 9, 13a; Plate 6 Fig. 1a; Plate 7 Figs. 7a, b

1935 *Amoeboceras (Amoebites) rasenense* Spath, p. 29, pl. 1, figs. 6 a, b (Holotype)

1951 *Amoeboceras (Amoebites)* aff. *rasenense* Spath; Waterston. pl. II, fig. 1.

Material: 11 specimens from Eathie, Cromarty; 1 and 1 *A*. cf. *rasenense* from Kintradwell; 2 *A*. cf. *rasenense* from Crackaig Links.

Holotype: Figured by Spath (1935), BM 50629a, from Market Rasen, Lincolnshire.

Description: All the specimens are badly flattened, though preservation of the Eathie specimens is good. Maximum diameter is 30 mm, with an umbilical ratio diameter of 33%. 2 specimens have reasonably preserved inner whorls, which display primaries resembling the inner early stages of *A. kitchini*. Most have sculpture preserved on only the outer whorl, where the primary ribbing becomes coarse and rectiradiate. There are about 35 primaries on the last whorl, becoming progressively more spaced with increasing diameter. At three-quarters whorl-height the ribs become quite strongly prorsiradiate, occasionally bifurcating, and ending in elongated ventro-lateral clavi. None of the specimens has the venter preserved, but a rather coarsely serrated keel is visible on most specimens.

Remarks: The Eathie specimens agree well with the holotype of *A. rasenense* in size, coiling and sculpture, and are virtually indistinguishable from the specimen figured by Waterston (1951, pl. II, figs. 1a, b), although this has a well preserved ventro-lateral shoulder with prominent tubercles (note: this specimen was referred to *A. kitchini* by Arkell & Callomon, 1963, p. 238). Of the other specimens, preservation is too poor to be certain of the identification, except one specimen from Kintradwell which is identical to the Eathie forms.

Range: At Eathie *A. rasenense* occurs with *Rasenia evoluta*, and separately with *Rasenioides*, indicating an upper Cymodoce Zone to early Mutabilis Zone age, and is associated with *A. kitchini*. At Kintradwell it is found with *R. evoluta*, and at Crackaig Links *A.* cf. *rasenense* occurs with *Xenostephanoides*, again suggesting a level close to the Cymodoce/Mutabilis boundary. At the type locality (Market Rasen) the Cymodoce Zone yielded common *A. rasenense* with *A. kitchini*.

Amoeboceras (Amoebites) cricki (Salfeld)

Plate 4 Figs. 10, 11

1914 *Cardioceras Cricki* Salfeld, p. 129

1963 *Amoeboceras (Amoebites)* cf. *cricki* (Salfeld); Arkell & Callomon, p. 239, pl. 32, figs. 25a-c

Material: 5 specimens; 1 from Kintradwell, 1 plus 2 *A*. cf. *cricki* from well 15/21a-25, 2 from 15/21a-11, and 1 from South Ferriby bed 14 (plus 2 *A*. cf. *cricki*, beds 14 and 20). 2 *A*. cf. *cricki* from 15/21a-29.

Type: Type series figured by Salfeld, 1915, pl. XIX, figs. 2-6

Description: Small, maximum diameter seen 20 mm, umbilical ratio c. 25%; at diameter 13 mm umbilical ratio c. 30%. Inner whorls finely ribbed, outer whorl with fine, sharp, rather dense primaries remaining straight to the beginning of the ventro-lateral shoulder. Here, up to every second primary bifurcates, the secondaries forming weak ventro-lateral clavi on the shoulders as they become strongly prorsiradiate sweeping onto the venter, joining the keel far in advance of their position on the sharp shoulders. The whorl section is compressed and fairly quadrate, the venter being flat with the keel raised to varying degrees, and very finely serrated.

Remarks: The Kintradwell specimen shows what may be the trace of a rostrum, but is badly flattened. The specimens from cored sections are often fragmentary, though all include some ventro-lateral portion: these are referred to *A. (A.)* cf. *cricki*. The South Ferriby specimens include two well preserved specimens and one ventral portion. One of these is a rather inflated and more coarsely ribbed variant, but is only the inner whorls; the other is closely similar to the specimen figured by Birkelund & Callomon (1985, pl. 9, fig. 13c) as *Amoeboceras* aff. *cricki* or cf. *A. schlosseri* (Wegele), but without such a raised keel.

Range: *A. cricki* is found in association with typical Cymodoce and Mutabilis Zone forms in the well sections, in the Cymodoce Zone at South Ferriby, and with *Rasenia evoluta* at Kintradwell.

Amoeboceras (Amoebites) beaugrandi (Sauvage)

Plate 4 Fig. 12

1871 *Ammonites beaugrandi* Sauvage, p. 349 (v. 19), p. 165, pl. 10, fig. 6 (v. 20)

1935 *Amoeboceras (Amoebites) beaugrandi* (Sauvage); Spath, p. 31, pl. 5, fig. 4; pl. 4, fig. 8

1985 *Amoeboceras (Amoebites)* cf. *A. (A.) beaugrandi* (Sauvage); Birkelund & Callomon; p. 23, pl. 4, figs. 6-8

Material: 8 specimens; 1 each from wells 15/21a-12 and 15/21a-25, and three each from Lothbeg Point and Crackaig Links; plus 1 *A.* cf. *beaugrandi* from Crackaig Links and 15/21a-4. Many crushed specimens from Lothbeg Point on bedding plane.

Holotype: Figured by Sauvage & Rigaux, 1871, pl. 10, fig. 6; holotype by monotypy.

Description: All badly flattened except one. Up to 30 mm diameter, umbilical ratio 30%. Coiling is evolute. Ribbing is rather fine, and generally dense; coarser varieties are represented. There are many secondaries, up to every second primary bifurcating at about two-thirds whorl-height, and usually forming weak ventro-lateral clavi as they become prorsiradiate onto the venter. They are separated from the finely serrated keel by a smooth band on each side.

Remarks: The material from Lothbeg Point was collected at the same locality as that described briefly by Callomon (in Arkell & Callomon, 1963, p.242), from the Loth River Shales. His assemblage included *A. (A.) beaugrandi, A. (A.)* sp. aff. *kitchini, Rasenia*? cf. *möschi* and *Aulacostephanus (Xenostephanoiodes)*? cf. *lindensis*; the present author recovered only *A. (A.) beaugrandi* along with numerous crushed *Amoebites* sp. indet., and a very large (6cm) *Inoceramus* and several small *Buchia* s.

A. (A.) cf. *beaugrandi* from 15/21a-4 is only a whorl fragment, but what there is bears close comparison with the other specimens. Those from Crackaig Links are associated with *A. (A.)* cf. *kitchini*, and characteristic Mutabilis Zone indicators *Aulacostephanoides* and *Aulacostephanites*. As pointed out by Birkelund & Callomon (1985, p. 24), the use of the name *A. beaugrandi* for microconchs from this level is largely conventional; these specimens are closer to the varieties figured by Spath (1935, pl. 4, fig. 8) as intermediates to *A. nathorsti* (Lundgren) than to the type.

Range: All the material occurs with indicators of the lower and middle parts of the Mutabilis zone.

Subgenus: *Euprionoceras* Spath, 1935

Type species. *A. (E.) kochi* Spath, 1935

Separated from *Amoebites* by Spath because of supposed phyletic affinities to the Upper Oxfordian subgenus *Prionodoceras*. It is stratigraphically between the *A. subkitchini/kitchini* group below, and the *A. elegans* group above, and the only notable character dividing it from these *Amoebites* is a reversion to simple secondary ribbing at the ventro-lateral shoulder rather than the accentuated clavi (Birkelund & Callomon, 1985).

Amoeboceras (Euprionoceras) kochi Spath

Plate 5 Figs. 1, 2a

1935 *Amoeboceras (Euprionoceras) kochi* Spath. p. 26, pl. 5, figs. 2a (Holotype), and b.

1935 *Amoeboceras (Amoebites)* cf. *elegans* and cf. *dubium* (Hyatt); Spath, p. 34, pl. 3, fig. 1

1976 *Amoeboceras (Euprionoceras) sokolovi* (Sokolov & Bodylevsky). Sykes & Surlyk, fig. 6G

1985 *Amoeboceras (Euprionoceras) kochi* Spath; Birkelund & Callomon, p. 26, pl.7, figs. 1-5, pl. 8, figs. 1-7

Material: 9 specimens; 7 (plus 1 *A.* cf. *kochi*) from 15/21a-25, 2 from West Garty, 1 *A.* cf. *kochi* from Crackaig Links. (Numerous poorly preserved specimens from West Garty are identified as *A.* cf. *kochi*.)

Holotype: Figured by Spath (1935), MGUH 8159, from Milne Land, East Greenland.

Description: All specimens badly flattened, usually quite fragmentary and often poorly preserved. The largest specimen has a diameter of c. 60 mm (umbilical ratio c. 30%); most specimens (core material) are between 25 mm and 35 mm diameter [m]. Ornamentation is fairly uniform at different diameters, though at earlier stages it is fine and close, later becoming more widely spaced. The ribs are sharp, single and straight up to the ventro-lateral shoulder where they become strongly prorsiradiate, this being the more pronounced in larger [M] specimens. Occasional specimens have frequent bifucating ribs; most have a few. At the ventro-lateral shoulder bullate tubercles may be developed on the ribs. None of the more complete specimens shows the venter, though a finely crenulate keel is sometimes visible in profile. Ventral impressions preserved on surfaces with numerous *A.* cf. *kochi* fragments show separation between the keel and the ribs, with a ratio of crenulae on the keel:ribs of 2:1.

Remarks: The core material and other microconchs (so referred only on size considerations, as no sutures are visible) agree well with those figured by Birkelund & Callomon (1985, pl. 8, figs. 5-7), and Spath's (1935) pl. 3, fig. 1 (*A.* cf. *elegans* and cf. *dubium*, referred to *A. kochi* by Birkelund & Callomon, 1985, p.26), in the inner whorls, while the outer whorls of many are indistinguishable from the outer whorl of *A. sokolovi* figured by Sykes & Surlyk. The only good [M] specimen, from West Garty, is close to the type; and *A.* cf.

kochi [M] from Crackaig Links is again close to Sykes & Surlyk's figure 6G (1976), but is too fragmentary to give an unequivocal identification. The remainder of the crushed specimens are too poorly preserved to be identified with more certainty than as *A.* cf. *A. kochi.*

Range: In 15/21a-25, *A. kochi* is found in association with *Aulacostephanites eulepidus*, and is just below unidentified coarsely ribbed *Aulacostephanus* s.s., indicating an basal Eudoxus Zone age. At West Garty also, poorly preserved *Aulacostephanus* s.s. sp. indet. accompany *A. kochi.* At Crackaig Links however, *A.* cf. *kochi* is associated with *Aulacostephanoides*, suggesting a middle or upper Mutabilis Zone age.

5.2 Superfamily: **PERISPHINCTACEAE** Steinmann, 1890

Family: **AULACOSTEPHANIDAE** Spath, 1924

[=Raseniidae Schindewolf, 1925]

Subfamily: **AULACOSTEPHANINAE** Spath, 1924

[incl. Pictoniinae Spath,1924; Raseniinae Schindewolf,1925; Ringsteadiinae Schneid,1939]

The Aulacostephaninae embraces *Pictonia*-like forms with evolute coiling, circular whorl-section and smooth, regular ribbing passing over the venter without interruption, to end forms of *Aulacostephanus* with compressed, angular whorl-sections and strong, straight ribbing interrupted by a deep groove on the venter.

The genera *Decipia-Ringsteadia-Pictonia-Rasenia-Aulacostephanus* are successive segments in a smoothly evolving lineage of perisphinctids. The boundaries between genera are arbitrary, representing no clear breaks in evolution (Callomon, 1981; Birkelund & Callomon, 1985). The constrictions and flared ribs considered characteristic of *Pictonia* macroconchs are absent in some varieties of most species, and already occur as early as late *Ringsteadia* at least up to *Rasenia cymodoce.* The microconchs intergrade more strongly yet, deviating little from a common isocostate morphology usually referred to *Prorasenia* Schindewolf, 1925, which ranges from latest Oxfordian to the lower Mutabilis Zone.

Earlier parts of the subfamily have traditionally been grouped around *Rasenia*, leading to later parts grouped around *Aulacostephanus*. A wealth of other generic names have arisen which are, as Arkell & Callomon (1963) note, based on insufficient material and stratigraphy, inadequate type specimens, and the requirements of phylogenetic theory. Grouping according to sculpture can be incorporated at subgeneric level.

The systematics of the Aulacostephanidae were discussed by Callomon (1981, p. 153) who discerns four branches with a common ancestor in the Middle Oxfordian *Perisphinctes*. From the oldest *Decipia-Ringsteadia-Pictonia-Rasenia* line, which terminates in the Cymodoce Zone, *Pachypictonia* diverged in the Upper Oxfordian, giving rise to the *Eurasenia/Prorasenia* group. The fine-ribbed *Rasenioides*, leading to *Aulacostephanites/Aulacostephanoides/Involuticeras*, split off from *Rasenia* s.s. in the lower Cymodoce Zone. In the upper Cymodoce Zone a third branch divided from *Rasenia* s.s., the coarser *Zonovia (uralensis)* group leading to *Xenostephanus* and eventually *Aulacostephanus* proper.

The *Rasenioides* group is envisaged to have colonized a sub-province intermediate between sub-Boreal and sub-Mediterranean, reaching the British area in the late Cymodoce Zone, and becoming so dominant as for Birkelund *et al.* (1983) to propose that the base of the Mutabilis Zone in Britain be drawn at the level where they replace *Rasenia* s.s.. *Xenostephanus*, with fully developed Aulacostephanid ribbing, occupied the Boreal Province, but is well known from the British lower Mutabilis Zone, well before the appearance of its direct descendant *Aulacostephanus* s.s. The latter appears suddenly to replace the fine-ribbed forms, (*Aulacostephanoides*) often with a sharp faunal break (the base of the Eudoxus Zone), illustrating rapid migration.

Genus: ***Pictonia*** Bayle, 1878

Type species. *Pictonia baylei* Salfeld, 1913 [=*P. cymodoce* Bayle (non d'Orbigny)]

Pictonia cf. ***densicostata*** Buckman, 1924

Plate 5 Fig. 3

cf.1924 *Pictonia densicostata* Buckman

cf. 1935 *Pictonia baylei* Salfeld; Spath, p.43, pl.8, figs.4a,b (referred to *P. densicostata* by Birkelund & Callomon, 1985, p.32)

Material: Numerous poorly preserved, fragmentary, badly flattened specimens [M], from South Ferriby (Bed 14).

Holotype: Figured by Buckman in his *Type Ammonites* (1924).

Description and remarks. All the macroconchs, often up to 100 mm+ diameter, are completly crushed and virtually impossible to collect. The inner whorls of these moderately evolute forms show sharp, straight primaries, which become trifurcate where the roots of the secondaries are exposed. Furcation point is about half-whorl height. The ribbing is very regular, and spacing quite distant, with strong constrictions with flared ribs on the apertural side; ribbing fades with increasing diameter.

Birkelund & Callomon (1985, p. 31) suggested that *P. normandiana* and *P. baylei* together would fit easily into the range of variability of *P. densicostata*; *P. normandiana* is much less regularly ribbed, and is possibly a senior synonym of *P. baylei*. Throughout beds 12, 14, 16 and 18 at South Ferriby there are crushed macroconchs of *Pictonia*. Callomon (in Birkelund & Callomon, 1985, p. 17) recognized the *P. densicostata* horizon (known from Britain and Normandy) marking the base of the Baylei Zone, and a higher horizon of *P. baylei* Salfeld, including *P. normandiana* Tornquist.

Range. Baylei Zone.

Genus: ***Rasenia*** Salfeld 1913

Type species. *Rasenia involuta* Spath

Within this genus Geyer (1961) identified six subgenera of *Rasenia* sensu stricto including *Zonovia, Eurasenia* and *Prorasenia*, with coarse and/or sharp ribs; *Involuticeras*, involute with a steep umbilical slope; and *Rasenioides* and *Semirasenia*, evolute with fine ribbing and a gentle umbilical slope. In discussion of the subdivision of *Rasenia*, Arkell & Callomon (1963) grouped the subgenera into microconchs and macroconchs. In order of decreasing coarseness of ribbing these are:

Microconchs.

1. *Prorasenia* Schindewolf 1925. Characterized by strong triplicate ribbing on the inner whorls reverting to biplicate perisphinctid on the final body chamber.

2. *Rasenia* sensu stricto. Fully grown at c. 40 mm diameter with strong unmodified ribbing to the end, and hence microconch. Primaries strong and sinuous, secondary ribbing fine and fasciculate. The inner whorls are well covered, involute and inflated.

3. *Rasenioides* Schindewolf 1925. Microconch subgenus characterized by very fine dense fasciculate ribbing [=*Prorasenioides* Schindewolf 1925].

Macroconchs.

4. *Zonovia* Sasonov 1960. Large, evolute, coarsely ribbed forms with smooth apertures.

5. *Eurasenia* Geyer 1961. Large, coarse forms between *Zonovia* and *Involuticeras*.

6. *Involuticeras* Salfeld 1913. Large, involute, compressed forms, finely ribbed on inner whorls, becoming smooth.

7. ?*Semirasenia* Geyer 1961. Arkell & Callomon (1963) raise doubts as to the validity of this subgenus due to the small size of the holotype of the type species, *Ammonites Mœschi* Oppel 1863, which is 45 mm in diameter and is described as displaying the last suture line and three-quarters whorl body-chamber, making it nearly complete, even though Geyer (1961) judges the final size to be "about 70 mm." Geyer places *Ammonites thermarum* into *Semirasenia* also, the holotype of which Arkell & Callomon (1963) suggest would fit equally well into *Rasenioides*; it is 20 mm in diameter with a nearly complete body-chamber.

Ziegler (1963) described a new species, *Rasenia (Semirasenia) askepta*, the holotype of which has a maximum diameter of 52 mm. Other specimens grouped with the same species have phragmocone diameters of 59 mm, c. 72 mm, and 110 mm. Geyer's (1961) emphasis on the late appearance of primaries in *Semirasenia* is hardly sufficient to imply subgeneric status: Ziegler suggested it may be warranted to classify all apparently macroconch species of *Rasenia* with fine ribs and a gentle umbilical slope with *Semirasenia*, but there is no proof or phylogenetic justification to do so. It is worth noting however, that the derivatives of the *Semirasenia* group comprise the macroconch subgenus *Aulacostephanoides*, and Birkelund *et al.* (1983) suggest that as the macroconchs of *Rasenioides*, *Semirasenia* could be made a subgenus or synonym of it. Herein, they will be grouped with *Rasenioides*, with accessory notes where appropriate.

Subgenus: ***Prorasenia*** Schindewolf 1925

Type species. *Prorasenia quenstedti* Schindewolf

Throughout the exposed Upper Oxfordian (Pseudocordata Zone) and Baylei Zone (Beds 2-18) at South Ferriby, nuclei betwwen 12 and 18 mm diameter occur in great profusion (Plate 2 Figs. 6-10). They are all distinguished by trifurcate branching of the ribs, and often bear constrictions and flared ribs. The whorls are moderately to rather depressed, and evolute. The whorl section is rounded with a rounded venter and lateral areas.

They are all certainly *Prorasenia* spp., but at this diameter are difficult to identify; it appears that *Prorasenia triplicata* (J. Sowerby) and *P. bowerbanki* Spath are both represented throughout in so far as the nuclei can be identified (the type of *P. triplicata* is 11 mm diam.), *P. bowerbanki* being recognized by earlier reversion to biplicate ribbing (for the whole of the body-chamber).

There are also several complete but flattened specimens bearing the whole or almost whole body-chamber, and these are described below.

Prorasenia bowerbanki Spath.

Plate 5 Fig. 4

1935 *Prorasenia bowerbanki* Spath; p. 43, pl. 14, figs. 3a, b (holotype)

1951 *Prorasenia bowerbanki* Spath; Waterston, pl. II, fig. 5

Material. One, bed 10 South Ferriby, 1 *P.* cf. *bowerbanki*, bed 14

Holotype: Figured by Spath (1935) B. M. 24712 from Wooton Bassett, Wiltshire.

Description. Diameter c. 30 mm. Inner whorls show fairly coarse bullate, straight primaries and the roots of trifurcate secondaries; in the last whorl the ribbing is distant and reverts to biplicate, with the bifurcation point at half-whorl height, and the primaries are not so bullate. The very end of the peristome is missing. The third primary from the end is preceded by a broad, slight constriction and a single secondary, followed again by a single secondary. The specimen agrees quite closely with the holotype.

Range. Callomon (Birkelund & Callomon, 1985, p. 32) remarked that at South Ferriby typical *P. bowerbanki* occurs in the Pseudocordata Zone, but not in the Baylei Zone. This specimen occurred about 0.5 m below the Pseudocordata/Baylei (=Oxfordian/Kimmeridgian) boundary. The specimen of *P.* cf. *bowerbanki* is from bed 14 near the base of the Baylei Zone, with *Pictonia* cf. *densicostata*, of which it may be the microconch.

Prorasenia aff. ***triplicata*** (J.Sowerby)

Plate 5 Fig. 5

aff. 1935 *Prorasenia triplicata* (Sowerby); Spath, p. 40, pl. 12, fig. 2, pl. 14, fig. 5

aff. 1951 *Prorasenia* aff. *triplicata* (J.Sowerby); Waterston, p. 44, pl. II, figs. 6, 7

Material. One, bed 18 South Ferriby.

Holotype: BM 48955 figured by J. Sowerby, 1815, pl. XCII, fig. 2, from Portland

Roads.

Description. The specimen is a complete microconch with the stump of a lappet. Diam. c. 30 mm. Inner whorls show coarse, straight, bullate primaries, and the roots of triplicate and biplicate secondaries. Unfortunately, about half the last whorl is missing, but what there is shows exceptionally bullate primaries, drawn into elongated, sinuous tubercles, very slightly prorsiradiate, carrying on past the furcation point at about half-whorl height. The secondaries are also sharp and coarse, bi- or triplicate for the first third of the last whorl. The next half-whorl is missing. At the end of the peristome, the last two primaries, now relatively diminished in relief, though still strong and coarse, bifurcate, then there is a single secondary before a collared aperture.

Remarks. This evolute irregularly ribbed form differs from *P. triplicata* principally in that, as far as is discernible with the state of preservation, the secondaries are not uniformly trifurcate. Waterston's (1951) *P.* aff. *triplicata* has three-quarters of the last whorl of body-chamber, on which coarse trifurcate ribbing is present for more than half (exactly the portion missing on this specimen). He also states "...the primary ribs of the inner whorls are raised to form strong primary ridges which die out before reaching the last whorl", and suggests a form transitional between *Prorasenia* and *Rasenia*. On this specimen the primary ridges are still definitely present at the start of the last whorl; the ribbing in general is reminiscent of *Rasenia*, if somewhat coarser and more distant.

Range. Found in bed 18, South Ferriby, top of the Baylei Zone; possibly a microconch for *Pictonia normandiana/baylei*.

Subgenus: ***Rasenia*** Salfeld, 1913

Type species. *Rasenia involuta* Spath.

Rasenia (Rasenia) sp. cf. ***inconstans*** Spath

Plate 5 Fig. 11

cf. 1935 *Rasenia inconstans* Spath, p. 45, pl. 8, fig. 7.

cf. 1935 *Rasenia* aff. *orbigny* (Tornquist) Spath, p. 43, pl. 9, figs. 3, 4

cf. 1935 *Rasenia orbigny* (Tornquist) var *ornata* Spath, p. 43, pl. 10, fig. 3

cf. 1935 *Pictonia* sp. juv.; Spath, pl. 8, fig. 5

cf. 1985 *Rasenia inconstans* Spath; Birkelund & Callomon, p. 33, pl. 12, fig. 4, pl. 13, fig. 5, pl. 14, figs. 2, 4

Material. 3; one each from 15/21a-4, 15/21a-12a, 15/21a-25.

Holotype of R. inconstans: MGUH 8187 figured by Spath, 1935, pl. 10, fig. 6 from Milne Land, East Greenland.

Description. The three specimens have diameters of 12 mm, c. 14 mm, and c. 9 mm. Only the outer whorls are preserved. Ribbing is straight, coarse and strong. Those from wells 15/21a-4 and 12a have short primaries on the umbilical slope, and long straight secondaries crossing the venter without interruption. One shows a distinct constriction and flared rib. On the specimen from 15/21a-25 the primaries are longer, furcation point about two-thirds whorl height. This is virtually identical to one of Spath's (1935, pl.8, fig.5) specimens.

Remarks: Birkelund & Callomon (1985) consider Spath's *R. orbignyi* (Tornquist) and *R. orbignyi* var. *ornata* with heavy bullate ribs and forms close to *Pictonia* (Spath's *Pictonia* sp. juv.) to all be variants of *Rasenia inconstans* Spath after studying rich material from one horizon in Milne Land, East Greenland.

Range: R. inconstans characterises the earliest *Rasenia*-bearing horizons in Milne Land (faunas 15 and 16) although the dividing line between *Pictonia* and *Rasenia* is somewhat arbitrary. These horizons are assigned to the lower Cymodoce Zone. Although the species has been described only from Milne Land, Birkelund & Callomon remarked that some crushed specimens in the Cymodoce Zone at South Ferriby are barely distinguishable. In the wells they may be associated with *Amoeboceras* cf. *subkitchini.*

Rasenia involuta Spath

Plate 5 Fig. 12

1935 *Rasenia involuta* Spath, p. 48, pl. 10, figs. 5a, b (holotype)

1951 *Rasenia* sp. nov (?). Waterston, pl. II, figs. 8a, b

1961 *Rasenia (Involuticeras) involuta* Spath; Geyer, p. 102, pl. 9, fig. 8, pl. 3, fig. 7

1978 *Rasenia (Eurasenia) involuta* Spath; Birkelund *et al.* p. 50, pl. 3, fig. 6

1983 *Rasenia involuta* Spath; Birkelund *et al.* figs. 3A-D, 4A-B

Material. 1 uncrushed from 15/22-5, 2 flattened fragments of *R.* cf.*involuta* from 15/21a-25; crushed *R.* cf.*involuta* from South Ferriby, bed 20.

Holotype: Spath selected only one of the specimens to which Salfeld had attatched the manuscript name *involuta* and this specimen (BM 50629b) is the holotype of *involuta* Spath, rather than the lectotype of *involuta* Salfeld.

Description. The well preserved microconch specimen from 15/22-5 shows about half the shell but has unfortunately been cut during core slicing. The whorls are visible almost to the centre of the umbilicus. Diameter would have been c.40mm. and therefore virtually complete (Arkell & Callomon, 1963, p. 221); the terminal constriction on the peristome is visible. The whorl section is oval; coiling is involute, the secondary ribs on the inner whorls are always covered and hence not visible in the umbilicus. On the body-chamber, the primaries become subdued and moderately flexuous rather than bullate, and most of the secondaries are intercalated. The bifurcation point is about one-third whorl height.

Remarks. The specimen differs from the type in having fewer and more distant secondaries, but can remain comfortably in *R. involuta* Spath. Of the 2 specimens of *R.* cf. *involuta* from 15/21a-25, the larger is of a similar size to that from 15/22-5, and is identical in sculpture. However, no inner whorls are preserved and therefore the degree of involution cannot be tested. The other specimen is smaller and shows the venter and one flank, again identical to that from 15/22-5 in ribbing, but finer at a comparable diameter. The South Ferriby specimens of *R.* cf. *involuta* are flattened nuclei, showing no secondaries in the umbilicus, and crushed macroconchs. The latter are therefore not *Rasenia* s.s., but *Involuticeras* (after Geyer), or *Eurasenia* after (Birkelund *et al.*) which are too poorly preserved or with too little sculpture to be certain, as only the body-chambers of specimens up to 100mm.+ are preserved.

Range. Upper Cymodoce Zone, "Involuta Subzone".

Rasenia evoluta Spath

Plate 5 Figs. 13-15

1935 *Rasenia evoluta* Spath; p. 48, pl. 14, figs. 6a, b

1978 *Rasenia (Zonovia) evoluta* Spath; Birkelund *et al.*, p. 44, pl. 1, figs. 4, 5; pl. 2, figs. 7-10, pl. 3, figs. 1-5, text figs. 5 (lectotype), 6

1983 *Rasenia evoluta* Spath; Birkelund *et al.*, p. 294, figs. 4C-E, 5A-C

1985 *Rasenia evoluta* Spath; Birkelund & Callomon, p. 36, pl. 19, fig. 1, pl. 20, figs. 1-7

Material. 18; 1 from 15/21a-12a, 13 from Kintradwell; 2 *R.* cf. *evoluta* from 15/22-5 and 1 from 15/21a-29, 2 [m] *R.* cf. *evoluta* from Eathie, plus 4[m] and numerous *R.* cf. *evoluta* [m] and [M] from South Ferriby (bed 20).

Lectotype: BM 39801 from Market Rasen, fauna B, horizon III (Birkelund *et al.*, 1978); labelled *R. evoluta* by Salfeld and designated lectotype by Birkelund *et al.*, 1978, p. 50.

Description. Largest [m] diameter 40 mm with the stump of a lappet; one specimen shows a broad constriction at the end at 25 mm diameter. Nearly all specimens are badly crushed with only one side preserved. Mean umbilical ratio 45%. Inner whorls show strong, bullate, prorsiradiate primaries, with very evolute coiling revealing bifurcate, trifurcate or fasciculate secondaries. On the last whorl, the primaries tend to become less flexuous, though still strongly bullate, and in the majority of specimens the secondaries remain fasciculate on the last whorl (cf. Birkelund *et al.*, 1983, figs. 5C and D).

Remarks. The specimens *R.* cf. *evoluta* from 15/22-5 are evolute with coarse distant ribbing crossing the venter without interruption and agree best with *R. evoluta.* That from 15/21a-29 is badly crushed; that from 15/21a-12a is a fragment of one whorl, with coarse, regular ribbing passing over the venter (cf. Birkelund & Callomon, 1985, pl. 20, fig. 5). Those from Eathie are badly flattened, retaining bullate primaries and fasciculate secondaries in the inner whorls, the secondaries remaining trifurcate on the last quarter-whorl with no intercalatories; these are all raseniid features rather than of *Xenostephanus,* which is very similar when crushed. At South Ferriby preservation is also poor. Macroconchs up to 200 mm + have finely ribbed inner whorls with rasenid ribbing, the roots of the secondaries are not covered by the younger whorls and are visible in the umbilicus. The shell tends to become smooth on the youngest part of the phagmocone, with blunt, rounded ribs reappearing on the body-chamber; whorl section oval (cf. Birkelund & Callomon, 1985, pl. 20).

Range. Top of the Cymodoce Zone, "Evoluta Subzone".

Rasenia sp.cf. ***coronata*** Mesezhnikov

Plate 5 Fig. 16

cf. 1969 *Rasenia coronata* Mesezhnikov, p. 109, pl. XIII, figs. 2a, b; pl. XIX, figs. 2, 3; pl. XX, figs. 2a, b (Holotype).

cf. 1976 *Rasenia* aff. *coronata* Mesezhnikov; Sykes & Surlyk, fig. 6D.

Material. One, crushed, 15/21a-29.

Holotype: Figured by Mesezhnikov (1969), 457/686, from Kheta River Basin, North Siberia.

Description and remarks. Diam. 32 mm, umbilical ratio 45%, whorl height 30%. The most remarkable features of the specimen are the 3 constrictions and flared ribs on the outer whorl; the earliest constriction has a flared rib on either side, the others have one only on the youngest side. Coiling is involute. The inner whorls are poorly preserved; the only point where the ribs are preserved at the umbilical seam shows that the primaries are rather long and straight with the roots of the secondaries just visible. On the outer whorl the ribbing is more clear; the primaries are again long and straight, furcation point between half and two-thirds whorl height. The primaries often bifurcate, and there are many distant, intercalated secondaries.

The specimen differs from *R. coronata* in two important respects. Firstly, the primaries are not distant from the umbilical seam, and secondly the bifurcating pattern is regular in a large proportion of the whorls. It agrees best with Mesezhnikov's pl. XIX, fig. 3, though again, in this the primaries are shorter and less regular.

Range. Birkelund *et al.* (1983, p. 290) report *R.* cf. *coronata* from the bottom of the Mutabilis Zone, with *Rasenioides*. In 15/21a-29, *R.* sp. cf. *coronata* occurs above R. cf. *evoluta*, suggesting a similar age.

Subgenus: ***Rasenioides*** Schindewolf (=*Prorasenioides* Schindewolf)

Type species. *Nautilus striolaris* Reinecke 1818

Rasenia (Rasenioides) lepidula (Oppel)

Plate 4 Fig. 13b; Plate 6 Figs. 1d, e; Plate 7 Fig. 7c

1863 *Ammonites lepidulus* Oppel, p. 242, pl. 67, figs. 4a, b (Holotype)

1961 *Rasenia (Rasenioides) lepidula* (Oppel); Geyer, p. 112, pl. 18, figs. 5, 6

1963 *Rasenia (Rasenioides) lepidula* (Oppel); Ziegler, p. 766, pl. 111, figs. 1-7

1963 *Rasenia (Rasenioides)* cf. and aff. *lepidula* (Oppel); Arkell & Callomon, p. 223, pl. 32, figs. 19-21

1983 *Rasenioides* cf. *lepidulus* (Oppel); Birkelund *et al.*, figs. 5D, E

Material. 4, plus fragments of *R.* cf. *lepidula*, from Eathie, and *R.* cf. *lepidula* from 15/22-5.

Holotype: Figured by Oppel (1863) ZU. ETH:VS. 230 from Baden (Aargau).

Description. All flattened and fragmentary. Max. diam. seen 20 mm. Narrow, sharp prorsiradiate primaries split into dense, rectiradiate secondaries with intercalatories; the trifurcation point at about one-quarter whorl height. As far as is visible, the ribs carry on onto the venter. Rather evolute coiling, and oval whorl section. The primaries are somewhat removed from the umbilical seam.

Remarks. These specimens are closely similar to those from Eathie figured by Ziegler (1963 , pl. 111, figs. 1-7); their diameter implies that the peristome is missing in all specimens (no septa are visible). The name *R. lepidula* is used for members of the *R. thermarum* group which are rather larger and more evolute then *R. thermarum*. Schneid (1939) stated that the distinguishing feature of *R. lepidula* was the persistence of sheaves of secondaries arising from each primary right to the end, whereas in *R. eulepida (=Aulacostephanoides eulepidus)* the ribbing reverts to simple bi- or triplicate near the aperture. This is impossible to ascertain with this material, but the phragmocone so closely resembles those already described that there can be little doubt as to their identification.

Range. The horizon from which these specimens came was described by Waterston (1951) as belonging to the"Uralensis" Zone. The dominance of *Rasenioides* places it in the lower Mutabilis Zone, with *R. askepta.*

Rasenia (Rasenioides) sp. aff. ***thermarum*** (Oppel)

Plate 6 Fig. 3

aff. 1863 *Ammonites thermarum* Oppel; p. 243, pl. 65, figs. 5a, b (Holotype)

aff. 1961 *Rasenia (Semirasenia) thermarum* (Oppel); Geyer, p. 106, pl. 18, fig. 9

aff. 1963 *Rasenia (Rasenioides) thermarum* (Oppel); Arkell & Callomon, p. 244, pl. 32, figs. 13-18.

Material. 1, from 15/21a-12a.

Holotype: Figured by Oppel (1865) ZU. ETH. VS 189 from Baden (Aargau).

Description and remarks. Diameter 19 mm, umbilical ratio 25%. Moderately evolute with close ribbing; primary ribs weak, bifurcating or with intercalatories; secondaries well developed, crossing the venter with no sign of weakening. Specimen appears to be complete; though no septa are visible, the presumed peristome bears a raised collar preceded by a broad constriction. On the last third of the outer whorl, following a flared rib and constriction, the ribbing becomes simplified, with long straight primaries bifurcating high up the whorl side or with intercalatories, and this is where it differs from *R. thermarum*; its size and involution put it in the *R. (R.) thermarum* group.

Range. Lower Mutabilis Zone, "Askepta" Subzone.

Rasenia (Rasenioides) cf. *möschi* (Oppel)

Plate 6 Figs. 1b, c

cf. 1863 *Ammonites Möschi* Oppel. p. 240, pl. 65. fig. 7 (Holotype)

cf. 1961 *Rasenia (Semirasenia) moeschi* (Oppel); Geyer, p. 105, pl. 8, figs. 7, 8

cf. 1963 *Rasenia (Semirasenia)* cf. *möschi* (Oppel); Ziegler, p. 767, pl. 111, figs. 8, 9.

Material. 4, from Eathie, all flattened.

Holotype: Figured by Oppel (1863) ZU. ETH. VS. 201, from Lagern (Aargau and Zurich).

Description and remarks. Max. diam. c. 32 mm. Shells involute, with very gentle umbilical slope. On the inner whorls the umbilical margin is smooth; on the outer whorl, narrow primaries appear, separated from the very dense fasciculate secondaries by a loss in relief. Ribbing prorsiradiate, the secondaries bending back again as they cross the rounded venter without interruption. Ziegler (1963) commented that at this diameter the peristome is probably missing, as according to Geyer (1961) the medium size in *R. möschi* is less than 70 mm. Ziegler's specimens also came from Eathie, and like these differ from the type in the primaries appearing on the phragmocone rather than being restricted to the second part of the body-chamber.

Range. Lower Mutabilis Zone, with *R. askepta.*

Rasenia (Rasenioides) askepta Ziegler

Plate 4 Fig. 13c; Plate 6 Figs. 4-6; Plate 7 Fig. 7d

1963 *Rasenia (Semirasenia) askepta* Ziegler, p. 768, pl. 111, figs. 10-11 (Holotype) and 12-13.

Material. 5, 1 uncrushed fragment from 15/21a-25, 4 from Eathie, more or less fragmentary, flattened, plus numerous *R.* cf. *askepta* from Eathie.

Holotype: 1859.33.3846, Royal Scottish Museum, Edinburgh, from Eathie, Cromarty.

Description. Largest diameter seen c. 60 mm. Whorl height c. 25%, umbilical ratio c. 25%. Umbilical slope gentle, whorl section oval - lateral parts of whorl and venter rounded. Coiling somewhat involute. Primaries distant from umbilical seam, narrow, bullate, prosiradiate. Secondaries dense and bent forwards, crossing the venter with very slight lessening in height or without interruption.

Remarks. There is some variability among the specimens grouped under this name.

The Eathie specimens have generally bullate primaries, with 5 or 6 secondaries arising from each on the outer whorls and agree well with the holotype. However, whereas one at 60 mm is almost smooth at the end, another is still strongly ribbed. Ziegler (1963) commented on the variable size of the phragmocone, between 59 and 110 mm. The diameter of the well preserved partially pyritised specimen from 15/21a-25 (Pl. 6, Figs. 5, 6) would have been c. 65mm, and it shows an interesting sculptural change with increasing diameter. The inner whorls have the sharp prorsiradiate primaries and densely arranged secondaries of the other specimens; on the outer whorl, the primaries become long and straight, though still removed from the umbilical seam, with secondaries arising from a furcation point at half whorl-height and with many intercalatories.This is very close to the later stages of *Aulacostephanoides mutabilis*, which is of greater size and has ribs interrupted on the venter.

Range. Characteristic of the lower part of the Mutabilis Zone, the "Askepta" Subzone (Birkelund *et al.*, 1983, and see discussion on p. 102-103).

The *Rasenia-Aulacostephanus* boundary.

Ziegler (1963) noted that of the species described as belonging to the subgenera *Rasenioides* and *Semirasenia*, with ribs crossing the venter, similar species exist with clear external interuptions of the ribs, these being grouped with *Aulacostephanus*. Geyer (1961) and Ziegler (1963) interpreted *Aulacostephanus* as a genus in which the majority of individuals in every population show interruption of external ribs throughout life. Arkell & Callomon (1963) drew the boundary such that forms assigned to *Aulacostephanus* have a smooth band on the venter in at least one stage of ontogeny. Working on a clearly conspecific collection, they noted that some specimens had a ventral smooth band and others did not, or had one at different stages of their ontogeny but not throughout. Attention was drawn to the fact that development also occurred in other characters of the sculpture, but not isochronously. The whorl section becomes more compressed and quadrate, with the venter tending to flatten. The inner whorls are markedly more evolute than in *Rasenia* so that secondary ribs on them are often partly exposed, with the umbilici consequently shallow, often with smooth gentle walls. Specimens of a contemporaneous population were grouped into species taking all their characters into account, with the arrangement of species into genera of secondary importance.

As mentioned in the biostratigraphic framework (p. 102) it seems that the finely ribbed forms (*Rasenioides*) and *Rasenia* s.s. were following separate evolutionary paths before the top of the Cymodoce Zone (Birkelund *et al.*, 1983). *Rasenia* and *Rasenioides* are independent groups phyletically, and to some extent provincially. *Rasenia* s.s. failed to colonize the Jura and southern Germany, the type area of *Rasenioides*. It persisted into the Mutabilis Zone, probably migrating further into the Boreal Realm, whereas in Britain the base of the Mutabilis Zone can easily be recognised by its sharp replacement by *Rasenioides*.

Replacing *Rasenioides* (the "late fine-ribbed rasenids" of Birkelund *et al.*, 1983) in the mid-Mutabilis Zone is *Aulacostephanoides* (the "early fine-ribbed Aulacostephanitids" of Ziegler, 1962) with the same dense, fine fasciculate ribbing, but now interrupted on the venter to give a smooth band. The macroconchs were all placed by Ziegler (1962) into *Aulacostephanoides* Schindewolf, the microconchs into a new subgenus *Aulacostephanites*. It seems highly probable that *Rasenioides* [m] to *Aulacostephanites* [m] and *Rasenioides* [M] (=*Semirasenia*) to *Aulacostephanoides* [M] represent one phyletic lineage. Ziegler (1963) recognized probable relationships at species level, from *Rasenioides lepidula* to *Aulacostephanites eulepidus*, from "*Semirasenia*" *askepta* to *Aulacostephanoides mutabilis*, and from "*Semirasenia*" *moschi* to *Aulacostephanoides variocostatus*.

Genus: ***Aulacostephanoides*** Schindewolf, 1925

Type species. *Ammonites desmonotus* Oppel, 1863

Conventionally, the *Aulacostephanoides* group has been treated as a subgenus of *Aulacostephanus*, as it shares the feature of secondaries which are interrupted on the venter. However the ribbing style and general morphological appearance is much closer to the ancestral *Rasenioides* than to *Aulacostephanus* s.s. This observation, coupled with the well documented morphological discontinuity between the youngest *Aulacostephanoides* and the oldest *Aulacostephanus* prompted Birkelund & Callomon (1985) to retain *Aulacostephanoides* as a separate genus.

The macroconchs cover a wide range of forms with two extremes:- 1) the *A. mutabilis* (Sowerby) group: large evolute planulates with a diameter of 200-300 mm, with well differentiated and prominent primaries (at least on the inner whorls;) and 2) the *A. desmonotus* (Oppel), *A. linealis* (Quenstedt) group: small, compressed, involute with diameters of 80-150 mm, and primaries tending to fade.

A. circumplicatus represents a morphologically intermediate group.

Stratigraphic information on the monographed material is scarce, and consequently there is little understanding of the extent to which intraspecific variability and stratigraphically successive stages are reflected by the morphological diversity, and Birkelund *et al.* (1983) suggested further investigation of the possibility that the *A. mutabilis* and *A. desmonotus* groups represent parallel lineages. The *linealis* and *desmonotus* groups may, therefore, have [M] and [m] forms independent of the well documented *mutabilis* [M] and *eulepidus* [m] groups.

Subgenus ***Aulacostephanoides***

Aulacostephanoides (Aulacostephanoides) mutabilis (Sowerby)

Plate 6 Fig. 7

1823 *Ammonites mutabilis* Sowerby, p. 145, pl. 405, fig. 1 (Holotype)

1962 *Aulacostephanus (Aulacostephanoides) mutabilis* (Sowerby); Ziegler, p. 62, pl. 4. figs. 1, 3-7, 9-11; text figs. 8a, 12, 18a, 32b + c, 33a, b + d

1963 *Aulacostephanus (Aulacostephanoides) mutabilis* (Sowerby); Arkell & Callomon, p. 229, pl. 31, fig. 3.

1983 *Aulacostephanoides mutabilis* (Sowerby); Birkelund *et al.*, p. 298, fig. 5I

1985 *Aulacostephanoides mutabilis* (Sowerby); Birkelund & Callomon, p. 42, pl. 22, figs. 1, 2

Material. 2 specimens from Crackaig Links plus numerous crushed specimens of *A.* cf. *mutabilis.*

Holotype: BM 43934, from Horncastle, Lincolnshire.

Description. Crushed, diameters c. 100 mm and c. 50 mm. Umbilical ratios 37% and 40%; whorl height 20%. Inner whorls evolute, quite finely ribbed, rather bullate prorsiradiate primaries trifurcating, with additional intercaleries, or with sheaves of fasiculate secondaries. On the outer whorl the primaries are still prominent with well-differentiated, fine, dense secondary ribbing visible to the end of the shell, with an occasional flared rib. The ribs become straighter and more distantly spaced with increasing diameter. Venters not visible.

Remarks. These specimens agreee best with those figured by Ziegler (1962 , pl. 4, figs. 1 and 4) in size, coiling and ribbing pattern. The numerous crushed specimens from Crackaig Links are almost invariably outer whorl fragments or ventral impressions. The whorl flanks are of a similar size to the outer whorl of the larger specimen, lacking primaries but with well defined secondaries; (cf.

Birkelund *et al.*, 1983, fig. 5I). All the venter impressions show clear interruption of the secondaries.

Range. Well documented as belonging to the middle and upper Mutabilis Zones in N.W.Europe.

Aulacostephanoides (Aulacostephanoides) sp.aff. ***mutabilis*** (Sowerby)

Plate 6 Fig. 8

Material. One fragment from 15/21a-11

Description and remarks. The specimen is partly well preserved and uncrushed. The long, straight primaries and intercalated secondaries are reminiscent of *Pictonia*, and there is also a constriction and flared rib considered characteristic of that genus. However, the marked lessening of rib height on the venter, and compressed whorl section would place it in *Aulacostephanoides*. The specimen of *A. (A.)* sp. nov? aff. *mutabilis* figured by Arkell & Callomon (1963, pl. 31, fig. 2) shares these features of compressed whorl section, well developed secondary ribbing with occaisional feeble constrictions and flared ribs.

Range. Occurs in the same core slice as *Xenostephanus thurrelli* - the age is lower to mid-Mutabilis Zone.

Subgenus: ***Aulacostephanites*** Ziegler

Aulacostephanoides (Aulacostephanites) eulepidus (Schneid)

Plate 5 Fig. 2b; Plate 6 Figs. 9, 10

1939 *Rasenia eulepida* Schneid, p. 146, pl. v, figs. 13, 13a (Holotype)

1962 *Aulacostephanus (Aulacostephanites) eulepidus* (Schneid); Ziegler, p. 44, pl. 1, figs. 1-16

1983 *Aulacostephanoides eulepidus* (Schneid); Birkelund *et al.*, figs. 5F, G

Material. 5 well preserved specimens from Crackaig Links section; 1 uncrushed *A.* cf. *eulepidus* from 15/21a-12a. Numerous crushed specimens from Crackaig Links, and from 15/21a-25. 1 *A.* cf. *eulepidus* from 15/21a-4.

Holotype: Figured by Schneid (1919) S. 146, Bamberg University, from Stublang (northern Frankenalbe, Germany).

Description. Diameters 20-33 mm (average c. 30 mm, as in the type). Umbilical ratio c. 45%; whorl height c. 30%. Very evolute, ribbing fine and dense; primaries prorsiradiate giving rise to sheaves of slightly rursiradiate fasciculate secondaries, degenerating towards the end.

Remarks. All the flattened material is indistinguishable from from Ziegler's (1962) figures 8, 9, 15 and Birkelund *et al.*'s (1983) fig. 5F. At Crackaig Links this species is remarkably numerous, every lamination at some horizons being covered with flattened specimens. The uncrushed specimen from 15/21a-12a has an almost rasenid venter and is best compared with the *A. (A.)* cf. *eulepidus* figured by Arkell & Callomon (1963, pl. 32, figs. 1-8). Like these it resembles *A. eulepidus* more closely than *Rasenioides* in coiling and ribbing style. This suggests a position close to the *Rasenia/Aulacostephanoides* boundary. This specimen is possibly transitional to to *A. (A.) ebrayoides* Arkell & Callomon, but can remain comfortably in *A. (A.)* cf. *eulepidus* (cf. Arkell & Callomon, 1963, pl. 32, 1a-b)
Range. As the microconch of *A. mutabilis*, the range is middle to upper parts of the Mutabilis Zone.

Aulacostephanoides (Aulacostephanites) cf. ***ebrayoides*** Arkell & Callomon

cf. 1963 *Alacostephanoides (Aulacostephanites) ebrayoides* Arkell & Callomon, p. 227, pl. 30, figs. 14-18, pl. 32, figs. 9, 10.

Material. One, Crackaig Links section (flattened).

Holotype of A. (A.) ebrayoides: MS 5, from Market Stanton, Lincolnshire. Thurell Collection.

Description and remarks. Diameter 30 mm, umbilical ratio c. 30%, whorl height c. 30%. Coiling evolute; ribbing dense, strong, sharp, straight triplicate or biplicate with intercaleries. Primaries have reduced contrast with secondaries compared to *A.eulepidus* and a furcation point close to the umbilical seam. Venter not visible. A little larger than the type material (holotype 26 mm.) but very close in all other respects.

Range. Associated with *Aulacostephanoides* and *Aulacostephanites*. Mid Mutabilis Zone.

Aulacostephanoides (Aulacostephanites) cf. ***desmonotus*** (Oppel)

Plate 6 Fig. 11

cf.1863 *Ammonites desmonotus* Oppel, p. 241, pl. 67, figs. 1a, b (Holotype)

cf.1962 *Aulacostephanoides desmonotus* (Oppel); Ziegler, p.50, pl. 2, figs. 13-15

cf.1963 *Aulacostephanus (Aulacostephanites)* aff. *desmonotus* (Oppel); Arkell & Callomon, p. 228, pl. 32, figs. 11, 12 cf.1983 *Aulacostephanoides* cf. *desmonotus* (Oppel); Birkelund *et al.*, figs. 5I, J, K, N.

Material. One, Crackaig Links [m].

Holotype of A. (A.) desmonotus: Figured by Oppel (1863) from Umgebung von Boll (White Jura δ, middle Schwabische Alb, Germany).

Description and remarks. Badly flattened; diameter c. 29 mm. Ribbing fine and dense; primaries very short and prorsiradiate. Long secondaries, arising near the umbilical seam in fasciculate sheaves, and rectiradiate. Venter not visible; it appears closely similar to *Rasenioides thermarum*, and it cannot be ascertained if it possessed the shallow umbilicus of *A. desmonotus*. The specimen agrees best with the flattened specimens from Wiltshire figured by Birkelund *et al.* (1983).

Range. Found with *A. eulepidus*, mid-Mutabilis Zone.

Aulacostephanoides (Aulacostephanites) cf. *linealis* (Quenstedt)

Plate 6 Fig. 12

cf.1888 *Ammonites linealis* Quenstedt, pl. 124, fig. 9 (Holotype)

cf.1962 *Aulacostephanoides linealis* (Quenstedt); Ziegler, p.54, pl. 2, figs. 1-10

cf.1983 *Aulacostephanoides linealis* (Quenstedt); Birkelund *et al.*, figs. 5L, M

Material. One, Crackaig Links [m].

Holotype of A. (A.) linealis: Figured by Quenstedt (1888) Ce 5/124/9, University of Tubingen; from White Jura δ (Schwabische Alb, Germany).

Description and remarks. Badly flattened, fragmentary. Diameter estimated to have been 35-40 mm. Coiling is very evolute; ribbing is exceptionally fine and dense. No primaries are visible; the secondaries are long and straight, starting at about one third whorl height. Venter not visible. Indistinguishable from the crushed specimens figured by Birkelund *et al.* (1983), and closely similar to Ziegler's (1962) figs. 5, 6, 9.

Range. Occurred with *A. eulepidus*.

Genus: *Aulacostephanus* Sutner & Pompeckj in Tornquist, 1896

Type species. *Ammonites pseudomutabilis* de Loriol

Ziegler (1962) recognized six subgenera in *Aulacostephanus*. *Aulacostephanoides* and *Aulacostephanites* are no longer included in it and have been dealt with above; *Pararasenia* was described as a possible descendant of the *Eurasenia* stock, and *Xenostephanus* was referred to only to describe several specimens from Lincolnshire (from where Arkell & Callomon were describing the subgenus at the time).

The first appearance of the "hoplitid" *Aulacostephanus* is abrupt, and in Britain is used to define the base of the Eudoxus Zone. The type species of *Aulacostephanus* s.s. and *Aulacostephanoceras (A. eudoxus)* define the macroconch and microconch groups respectively of the line, as recognized by Ziegler. Birkelund & Callomon's (1985) remark that of the species retained by Ziegler some reflect age differences, and some intraspecific variability, has yet to be worked out properly. The genus is now divided into four subgenera:

1. *Xenostephanoides* Arkell & Callomon 1963. Type species *Aulacostephanus (Xenostephanoides) thurrelli* Arkell & Callomon. Microconch subgenus; coiling evolute, particularly on inner whorls; whorl-section rounded, quadrate. Short bullate primaries with sheaves of strong, straight secondaries often separated from the primaries by a smooth band on the flanks. The strong ribbing style is already much more like the "hoplitid" one of later aulacostephanids than the sinuous rasenid one characteristic of species with which it co-exists. It may revert to simple biplication on the body-chamber. The venter carries a smooth band or groove.
2. *Xenostephanus* Arkell & Callomon 1963. Type species *Aulacostephanus (Xenostephanus) ranbyensis* Arkell & Callomon. Macroconch subgenus; coiling stout, depressed and evolute, particularly on the inner whorls. Primaries tending to extreme bullae on the umbilical margin and secondaries strong, triplicate, with intercalatories fusing to primaries or separated by smooth band on the inner and middle whorls. Venter flat with smooth band or groove. On the body-chamber the whorl-section becomes round and ribbing passes over the venter without interruption; primary ribs biplicate or become single widely spaced ridges.
3. *Aulacostephanoceras* Ziegler 1962. Type species *Ammonites eudoxus* d'Orbigny. Microconch subgenus with steep umbilical wall and strong, coarse secondaries; bi- or triplicate. As a rule evolute with lappets.
4. *Aulacostephanus* Sutner & Pompecj in Tornquist, 1896. Macroconch subgenus with steep umbilical wall; coarse sculpture. Inner whorls indistinguishable from those of the microconchs; evolute, strongly ribbed to c. 100 mm then becoming smooth.

Subgenus: ***Xenostephanoides*** Arkell & Callomon, 1963

Aulacostephanus (Xenostephanoides) thurrelli Arkell & Callomon

Plate 7 Figs. 1-3

1963 *Aulacostephanus (Xenostephanoides) thurrelli* Arkell & Callomon, p. 230, pl. 30, figs. 1 (Holotype) and 2-3

Material. 2 specimens, from well 15/21a-25 and 15/21a-11; plus 1 *A.* cf. *thurrelli* from 15/21a-25 and 2 from Crackaig Links.

Holotype: Figured by Arkell & Callomon (1963) R11, from Ranby, Lincolnshire. Thurrell Collection.

Description. Both are fragmentary - one being a flattened but rather well preserved half whorl, the other an uncrushed quarter-whorl. Quite sharp, coarse, straight primaries and bifid secondaries occur, widely spaced without intercaleries, and exceptionally strong and coarse. They are interrupted by a slight groove on the venter on the 15/21a-11 specimen (the other not having venter preserved).

Remarks. Although fragmentary, these two specimens are so close to the paratype (Arkell & Callomon, 1963, pl.30, fig. 2) that they can be named with confidence. The specimen *A.* cf. *thurrelli* from 15/21a-25 is badly crushed and represents only the inner whorls. Those from Crackaig Links are also badly flattened, but in evoluteness and sculpture resemble the holotype closely.

Range. The specimen from 15/21a-11 occurs in the same core slice as *Aulacostephanoides* sp. aff. *mutabilis*, and that from 15/21a-25 occurs just below *Rasenioides askepta*; this suggests a level in the lower part of the Mutabilis Zone. The Crackaig Links specimens are also associated with a lower to mid-Mutabilis Zone fauna.

Aulacostephanus (Xenostephanoides) cf. ***lindensis*** Arkell & Callomon

Plate 7 Fig. 4

cf.1963 *Aulacostephanus (Xenostephanoides) lindensis* Arkell & Callomon, p. 231, pl. 30, figs. 4-13 (fig. 10 = Holotype)

Material. One fragment, well 15/22-5.

Holotype of A. (X.) lindensis: MS 13, from Market Stanton, Lincolnshire. Thurrell Collection.

Description and remarks. One half whorl, uncrushed but with lateral damage. Whorl-section slightly depressed. Ribbing is finer than in *A. (X.) thurrelli*, though still moderately strong with three or four secondaries per primary. The venter is

wide and flat with a narrow smooth band. The specimen is slightly coarser than the inner whorls figured by Arkell & Callomon (pl. 30, figs. 13a, b), the ribbing pattern most closely resembles their pl. 30, fig. 11; the paratypes display enough variation to tenuously include the specimen.
Range. Lower part of the Mutabilis Zone.

Subgenus: ***Aulacostephanoceras*** Ziegler, 1962.

Aulacostephanus (Aulacostephanoceras) cf. ***eudoxus*** (d'Orbigny)

Plate 7 Fig. 5

cf.1850 *Ammonites eudoxus* d'Orbigny, p. 552, pl. 213, figs. 5, 6 (Lectotype)
cf.1962 *Aulacostephanus (Aulacostephanoceras) eudoxus eudoxus* (d'Orbigny); Ziegler, p. 80, pl. 5, figs. 18-24, pl. 7, figs. 1-13, text-figs. 9g, h, 13a, 15b, 19, 40d-g, 42, 79.
cf.1983 *Aulacostephanus eudoxus* (d'Orbigny); Birkelund *et al.*, figs. 6B, C.
cf.1985 *Aulacostephanus eudoxus* (d'Orbigny); Birkelund & Callomon, p. 44, pl. 23, figs. 1-3.
Material. 4, all flattened; 3 from West Garty section, 1 from 15/21a-25.
Lectotype: Designated by Ziegler (1962 , p. 80). D'Orbigny Collection, no. 4605, Mus. d'Hist. Nat., Paris, Lab. de Paleontologie; from St. Jean d'Angely (Charente Maritime, France).
Description and remarks. All specimens very poorly preserved. West Garty specimens all c. 45 mm diameter; one is apparantly complete, showing a ventral lappet. Coiling is quite involute, but the ribbing style is very similar to that in *A. eudoxus* with strong, very coarse secondaries, two or three per primary. The preservation is far too poor to give a certain identification, but the specimens are certainly *Aulacostephanus (Aulacostephanoceras)*, and what there is of the sculpture fits best with *A. eudoxus*. The 15/21a-25 specimen is smaller, and is only a whorl flank; (cf. Ziegler, 1962 ., pl. 7, fig. 9).
Range. Eudoxus Zone.

Aulacostephanus (Aulacostephanoceras) sp. indet.

cf. 1962 *Aulacostephanoceras volgensis* (Vischniakoff); Ziegler, pl. 9, fig. 7
Material. One, 15/21a-25.

Description and remarks. Diameter c. 50 mm Crushed and fragmentary. Coiling moderately evolute. Primaries elongated and sharp, slightly prorsiradiate; long, fine rectiradiate secondaries, most of which are intercalatories with only one or two arising from each secondary. The ribbing is rather finer than in *A.volgensis* figured by Ziegler, but not beyond what might be accepted within the range of variability.
Range. Eudoxus Zone.

Genus: ***Aulacostephanus*** Tornquist, 1896

Aulacostephanus sp. cf. ***yo*** (d'Orbigny)

Plate 7 Fig. 6

cf. 1962 *Aulacostephanus yo* (d'Orbigny); Ziegler, pl. 18, fig. 7

Material. One, 15/21a-25, flattened.

Holotype of A. yo: Figured by D'Orbigny, 1850, pl. 210. No. 4610, Mus. d'Hist. Nat., Paris, Lab. de Paleontologie; from Mauvages (Meuse, France.)

Description and remarks. Diameter c. 75mm, umbilical ratio c. 10%. Virtually oxycone shell; very little sculpture preserved, but quite fine rectiradiate secondaries visible at the outer margin of much of the outer whorl. Callomon & Cope (1971) remark that *A. yo* appears to be restricted to the Paris Basin and N.W. Germany. This specimen may extend that geographical range, but preservation is too poor to give any valid sort of identification.

Range. Eudoxus Zone.

cf. <u>Aulacostephanoides (Aulacostephanites) linealis</u>

(Quenstedt) in Ziegler, 1962, pl. 2, figs. 1-10

cf. <u>Aulacostephanoides (Aulacostephanites) desmonotus</u>

(Oppel) in Ziegler, 1962, pl. 2, figs. 13-15

6. PALYNOLOGY

6.1 DINOFLAGELLATE CYST SYSTEMATICS.

No detailed systematic study has been carried out in the course of this project, and no new taxa are herein formerly erected. In the South Ferriby section, and in the core material from the seven wells under palynological consideration in the present work, over 50 taxa of dinoflagellate cyst were identified, and these are listed alphabetically (after genus) below. References for author citations of the dinoflagellate cyst species mentioned may be found in Lentin & Williams (1989). Numbers following certain taxa refer to their position on the range chart (Fig. 3.8).

Adnatosphaeridium caulleryi (Deflandre, 1938b) Williams & Downie, 1969 [8]
Aldorfia dictyota subsp. *dictyota* (Cookson & Eisenack, 1960b) Davey, 1982b
Aldorfia dictyota subsp. *papillata* (Gitmez, 1970) Davey, 1982b
Aldorfia dictyota subsp. *pyra* (Gitmez, 1970) Davey, 1982b [15]
Apteodinium granulatum Eisenack, 1958
Atopodinium cf. *prostatum* Drugg, 1978
Chytroeisphaeridia chytroeides (Sarjeant, 1962a) Downie & Sarjeant, 1965 emend. Davey, 1979d
Chytroeisphaeridia mantelli Gitmez & Sarjeant, 1972
Cleistosphaeridium ehrenbergii (Deflandre, 1947) Davey *et al.*, 1969 [7]
Cleistosphaeridium polyacanthum Gitmez, 1970
Cleistosphaeridium polytrichum (Valensi, 1947) Davey *et al.*, 1969
Cleistosphaeridium tribuliferum (Sarjeant,1962a) Davey *et al.*, 1969 [10]
Cleistosphaeridium varispinosum (Sarjeant, 1959) Wodlam & Riding, 1983
Cribroperidinium globatum (Gitmez & Sarjeant, 1972) Helenes, 1984 [9]
Cribroperidinium cf. *granuligerum* (Klement, 1960) Stover & Evitt, 1978
Cribroperidinium longicorne (Downie, 1957) Lentin & Williams, 1985 [4]
Ctenidodinium chondrum Drugg, 1978 [17]
Cyclonephelium distinctum Deflandre & Cookson, 1955
Dictyopyxis areolata Cookson & Eisenack, 1960b
Egmontodinium ovatum (Gitmez & Sarjeant, 1972) Riley, 1979
Endoscrinium galeritum (Deflandre, 1938) Vozzhennikova, 1967 [21]
Endoscrinium luridum (Deflandre, 1938) Gocht, 1970b [16]
Epiplosphaera reticulospinosa Klement, 1960

Escharisphaeridia pocockii (Sarjeant, 1968) Erkmen & Sarjeant, 1980

Glossodinium dimorphum Ioannides et al., 1977 [3]

Gonyaulacysta jurassica subsp. *jurassica* (Deflandre, 1938) Norris & Sarjeant, 1965 emend. Sarjeant, 1982 [12]

Gonyaulacysta jurassica subsp. *jurassica* var. *longicornuta* Sarjeant, 1982 [20]

Gonyaulacysta nuciformis (Deflandre, 1938) Sarjeant, 1969

Hexagonifera jurassica Gitmez & Sarjeant, 1972

Hystrichodinium pulchrum Deflandre, 1935 [6]

Hystrichosphaeridium petilum Gitmez, 1970 [22]

Leptodinium mirabile Klement, 1960 emend. Sarjeant, 1984a

Leptodinium subtile Klement, 1960

Occisucysta balia Gitmez, 1970

Occisucysta monoheuriska Gitmez & Sarjeant, 1972

Oligosphaeridium pulcherrimum (Deflandre & Cookson, 1955) Davey & Williams, 1966b

Pareodinia ceratophora Deflandre, 1947c emend. Gocht, 1970b

Perisseiasphaeridium pannosum Davey & Williams, 1966 [1]

Perisseiasphaeridium ingegerdii Nøhr-Hanson, 1986 [2]

Prolixosphaeridium granulosum (Deflandre, 1937b) Davey *et al.*, 1966 [19]

Prolixosphaeridium parvispinum (Deflandre, 1937b) Davey *et al.*, 1966

Rhynchodiniopsis cladophora (Deflandre, 1938b) Below, 1981a [13]

Scriniodinium crystallinum (Deflandre, 1938b) Klement, 1960 [14]

Sentusidinium sp. ? *rioulti* (Sarjeant, 1968) Sarjeant & Stover, 1978 [24]

Sirmiodiniopsis orbis Drugg, 1978

Sirmiodinium grossi Alberti, 1961 emend. Warren, 1973 [18]

Stephanelytron scarburghense Sarjeant, 1961 emend. Stover *et al.*, 1977 [25]

Subtilisphaera paeminosa (Drugg, 1978) Bujak & Williams, 1983

Systematophora areolata Klement, 1960 [5]

Systematophora sp. A [23]

Tubotuberella apatella Cookson & Eisenack, 1960 [11]

Valensiella ovula (Deflandre, 1947) Eisenack, 1963

Contaminants of the *Spiniferites ramosus* group (Ehrenberg, 1838) Loeblich & Loeblich, 1966 were also encountered, and are discussed below.

6.2 SYSTEMATIC DISCUSSION OF DINOFLAGELLATE CYSTS.

Division **PYRRHOPHYTA** Pascher 1914

Class **DINOPHYCEAE** Fritsch 1929

Order **PERIDINIALES** Haeckel 1894

Genus ***Adnatosphaeridium*** Williams & Downie, 1966

Adnatosphaeridium caulleryi (Deflandre) Williams & Downie, 1969

Plate 1 Figs. 1-3

Description: Chorate cyst, with spherical to ovoidal shell. Periphragm drawn into numerous, extremely variable, processes; these are solid and distally closed, often branching and distally joined, sometimes assuming ring-like forms. Individual, unconnected processes are of approximately the same length as the others. Archaeopyle apical with zig-zag margin. Range of length 46-60 μ; breadth 43-50 μ; length apex missing (Fig. 2) 43 μ (10 specimens measured).

Observed range: Baylei to Mutabilis Zones.

Remarks: This distinctive species is prominent throughout the section examined up to the lower part of the "δ Sand". Erkmen & Sarjeant (1980, p. 69) remark on the inflated range attributed to this *A. caulleryi* by misidentification of other species with complex processes, and describe it as a good marker for latest Callovian and Oxfordian assemblages. They refer the Kimmeridgian records (Deflandre, 1941, p. 21 and Downie, 1957, p. 428) to *Systematophora*, and many of the specimens in this section are impossible to assign to either genus due to damage or masking by extraneous debris. However, the specimens here assigned to *A. caulleryi* represent an extension to its known range into the early and mid-Kimmeridgian.

Genus ***Aldorfia*** Stover & Evitt, 1978.

Aldorfia dictyota subsp. ***pyra*** (Gitmez) Davey, 1982b

Plate 1 Fig. 4

Description: Shell large, oval with a strong apical horn and rounded antapex. Divided by a broad cingulum into approximately equal epitheca and hypotheca. The endophragm follows the periphragm other than at the apex, where the endoblast is barely prominent. Archaeopyle is precingular. Figured specimen (slide 15/21-25 8403'); overall length 106 μ, breadth 75 μ, horn length 16 μ.

Observed range: Baylei to mid-Mutabilis Zones.

Remarks: The range top of *A. dictyota pyra* is a marker for the top of the

Stephanelytron scarburghense (Ss) Subzone of the *Endoscrinium luridum* (El) Zone (see Fig. 2) of Poulsen (in press). The range top is documented as mid-Mutabilis Zone in Lincolnshire (Riding, 1987) and Dorset (Riding & Thomas, 1988).

Genus ***Chytroeisphaeridia*** Sarjeant, 1962b emend. Downie, Evitt & Sarjeant, 1963.
Chytroeisphaeridia chytroeides (Sarjeant) Downie & Sarjeant emend. Davey, 1979d.

Plate 1 Fig. 5

Description: Shell subspherical, surface smooth, frequently folded. No indication of tabulation or a cingulum; the apical portion is often lost in archaeopyle formation. Length, apex lacking 25-50 μ; breadth 25-70 μ. Figured specimen, length 62.5 μ; breadth 56 μ.

Observed range: Baylei to Eudoxus Zones.

Remarks: Occurs in moderate abundance in all Kimmeridgian assemblages from onshore and offshore.

Chytroeisphaeridia mantelli Gitmez & Sarjeant, 1972

Description: The periphragm bears an ornamentation of rounded tubercles, coarse grana and verrucae. A tabulation is indicated only by slits extending posteriorly from an apical archaeopyle, and a faint indication of a cingulum in some specimens. Length, 25-70 μ; breadth 30-60 μ (6 specimens measured).

Observed range: Baylei to Eudoxus Zones.

Genus ***Cleistosphaeridium*** Davey, Downie, Sarjeant & Williams, 1966

Cleistosphaeridium ehrenbergii (Deflandre) Davey *et al.*, 1969.

Plate 1 Fig. 6

Description: Chorate cyst, shell subspherical, surface smooth with numerous (30-40) simple, straight, solid, conical and distally closed processes. The archaeopyle is apical. Figured specimen: length, apex lacking, 19 μ; breadth 28 μ; length of processes upto 20 μ.

Observed range: Baylei to Mutabilis Zones.

Remarks: Gitmez (1970) notes that this chorate cyst is more abundant in Dorset assemblages than in those from Scotland, and, though it is common, it never reaches great abundance in the offshore assemblages.

Cleistosphaeridium tribuliferum (Sarjeant) Davey et al., 1969

Plate 1 Figs. 7,8

Description: Chorate cyst, shell smooth, subspherical to ovoidal in shape, bearing moderately numerous (20-?50) conical, hollow, distally closed and recurved processes. An apical archaeopyle is present. Length, 30-35 μ; breadth, 20-25 μ; process length, 15-20 μ.

Observed range: Baylei to Mutabilis Zones.

Remarks: This species is moderately abundant throughout the section up to the "δ Sand", and very common in the Baylei Zone. It is comparable to *Hystrichosphaeridium petilum* (see p. 89) but has more numerous processes which are distally closed and proportionately shorter.

Genus ***Cribroperidinium*** Neale & Sarjeant, 1962 emend. Davey, 1969a emend. Sarjeant, 1982b emend. Helenes, 1984.

Cribroperidinium globatum (Gitmez & Sarjeant) Helenes, 1984

Plate 1 Fig. 9

Description: Proximate cyst, with subspherical to ovoidal shell and a strong apical horn. A narrow cingulum divides the theca into a longer epitract, sometimes with a precingular archaeopyle; and a dome-shaped hypotract. Overall length (figured specimen - slide 15/21-25 8270'), 87.5 μ; breadth 62.5 μ; length of apical horn 12.5 μ.

Observed range: Baylei to Eudoxus Zones.

Remarks: This species occurs rather infrequently throughout the section.

Cribroperidinium cf. ***granuligerum*** (Klement) Stover & Evitt, 1978

Plate 1 Fig. 11

Description: Shell subspherical with strong apical horn. A narrow cingulum divides the shell into a longer, somewhat conical epitract, and a shorter, rounded hypotract. The endophragm is densely granular. There is a precingular archaeopyle (visible on the figured specimen, slide 15/21-25 8270'). Figured specimen: overall length 81 μ; breadth 82 μ; horn length 7.5 μ.

Observed range: Baylei to Eudoxus Zones.

Remarks: In the figured specimen the position of the precingular archaeopyle is visible; the operculum appears to still be attatched and there is some secondary tearing of the cyst. This species occurs only infrequently. It differs from *C.*

granuligerum in that the small spines on the sutures are missing - this may be a preservational effect.

Cribroperidinium longicorne (Downie) Lentin & Williams, 1985

Plate 1 Fig. 12

Description: Shell polygonal in shape, with a long apical horn and conical hypotract divided from the longer epitract by a narrow cingulum. The sutures bear short crests. A precingular archaeopyle is sometimes present. The apical horn is approximately one third of the overall length. Range of overall length 95-108 μ; breadth 50-62 μ; horn length 28-34 μ (4 specimens measured).

Observed range: Cymodoce to Eudoxus Zones.

Remarks: The range base of *C. longicorne* at the base of the Cymodoce Zone is a marker for the base of the Ss Subzone and the base of the El Zone (Riding & Thomas, 1988, Poulsen, in press) and the findings of the present study concur with this.

Cribroperidinium sp. A.

Plate 1 Fig. 10

Description: The shell is ovoidal in shape, with a strong apical horn. A broad cingulum divides the cyst into a longer epitract and a shorter hypotract, which bears a flange over the antapex. There is a precingular archaeopyle. Length (figured specimen) 106 μ, breadth 75 μ, horn length 22 μ.

Observed range: 15/21-25 8270' (Mutabilis Zone).

Remarks: The specimen most closely resembles *C. auctifictum* (Brideaux, 1971) Stover & Evitt, 1978, although this species often has a longer hypotract than epitract (Helenes, 1984), and is characteristic of the Albian. The specimen could be a contaminant, as this sample also contains specimens of the *Spiniferites ramosus* group, of Cretaceous or Tertiary age (see below).

Genus ***Ctenidodinium*** Deflandre, 1931b emend. Sarjeant 1966b and 1975a emend. Woollam, 1983 emend. Benson, 1985

Ctenidodinium chondrum Drugg, 1978

Plate 1 Fig. 13

Description: Shell oblate, sometimes with a low apical projection. The distinct sutures are unornamented. Shell wall thin, and usually bearing fine grana.

Archaeopyle style is epicystal, separating just anteriorly to the narrow cingulum. Cyst length 60-85 μ; breadth 70-90 μ (10 specimens measured). Figured specimen (slide 15/21-25 8403'); epicystal archaeopyle, breadth 84 μ.

Observed range: Baylei to Eudoxus Zones.

Remarks: This species is more prominent in the early Kimmeridgian (i.e. Baylei and Cymodoce Zones) than in younger parts of the section. A good Kimmeridgian marker species.

Genus ***Endoscrinium*** (Klement) Vozzhennikova, 1967

Endoscrinium galeritum (Deflandre) Vozzhennikova, 1967

Plate 1 Fig. 14

Description: Broadly ovate theca, epitheca in the form of a truncated cone, the hypotheca more rounded. The periphragm forms an enclosing membrane with a protuberant portion capping the antapex. The thecal membrane is subject to considerable folding which may give the impression of a broad longitudinal furrow (as in the figured specimen, slide 15/21-25 8403'). Overall length 76-84 μ, breadth 85-93 μ; endoblast length 62-70 μ, breadth 63-70 μ (12 specimens measured).

Observed range: Baylei to lower Mutabilis Zones.

Remarks: The range top of *E. galeritum* is given in Riding & Thomas (1988, p. 72) as within the Cymodoce Zone, representing an extension from its apparant extinction in the Baylei Zone (Gitmez & Sarjeant, 1972; Riding, 1987). However, Wollam & Riding (1983) reported its occurence up to the Eudoxus Zone (qualified as rare or uncertain) and in Block 15/21 it ranges up to the lower Mutabilis Zone. Riding & Thomas' (1988) zonation uses *E. galeritum* as a marker for the top of their "a" Subzone of the El Zone at the top of the Cymodoce Zone. This scheme is clearly untenable for Block 15/21 (see Fig. 3.5).

Endoscrinium luridum (Deflandre) Gocht, 1970b

Plate 1 Fig. 15

Description: Subspherical to ovate theca, divided into approximately equal epitract and hypotract, both of which are rounded, by a moderately broad cingulum. The periphragm forms an enclosing membrane, folded to form a funnel-like protuberance on the antapical dorsal side (see figured specimen, slide 15/21-25 8403'). Figured specimen: overall length 94 μ, breadth 81 μ; endoblast length 80

μ, breadth 56 μ. Range of length: 88-96 μ, breadth 76-83 μ; endoblast length 74-82 μ, breadth 53-57 μ (10 specimens measured).
Observed range: Baylei to Eudoxus Zones.
Remarks: This species occurs faily frequently throughout, being more common in the Cymodoce Zone.

Genus ***Glossodinium*** Ioannides *et al.*, 1974 emend. Courtinat, 1980

Glossodinium dimorphum Ioannides *et al.*, 1977

Plate 2 Fig. 6

Description: In apical or antapical view it appears circular; in dorsal or ventral view appears subrhombahedral in outline. A broad cingular zone divides the cyst into approximately equal epitract and hypotract, the former ending in a broad, irregularly-shaped horn. The cingulum itself is bordered by folded crests. The endoblast is in close contact with the folded periphragm, and fills the pericoel except in the apical region. A precingular archaeopyle is sometimes present. Overall length 98-112 μ; breadth 80-94 μ; horn length 17-21 μ (4 specimens measured)
Observed range: Cymodoce to Eudoxus Zones.
Remarks: Occurs infrequently in small numbers.

Genus ***Gonyaulacysta*** Deflandre, 1964 emend. Sarjeant, 1969 emend. Stover & Evitt, 1978 emend. Sarjeant, 1982b.

Gonyaulacysta jurassica subsp. ***jurassica*** Deflandre, 1938b

Plate 2 Figs. 1-3

Description: Proximate cyst with polygonal outline, and long apical horn. A broad cingulum divides the theca into a rhomb-shaped hypotract and a longer, conical to rounded epitract. The sutures bear short crests and the periphragm appears to form a fringe in dorsal or ventral view. A precingular archaeopyle is developed. Range of overall length 75-100 μ; breadth 56-69 μ; horn length 16-25 μ, upto one quarter of overall length (8 specimens measured).
Observed range: Baylei to Eudoxus Zones.
Remarks: The last occurrence of common *G. jurassica jurassica* is taken as a marker for the base of the El Zone (base Cymodoce chronozone) by Poulsen (in press). In Block 15/21 *G. jurassica jurassica* is common up to the mid-Cymodoce Zone.

Gonyaulacysta jurassica subsp. ***jurassica*** var ***longicornuta*** Sarjeant, 1982b

Plate 2 Figs. 4,5

Description: Shell polygonal, more elongated than in *G. jurassica jurassica.* A broad cingulum divides a short rounded hypotract from a very long, truncated conical epitract which forms approximately two thirds of the overall length. This is capped by a broad, tapering horn. A precingular archaeopyle is developed. Range of overall length 81-94 μ; breadth 44-50 μ; length of horn 19-25 μ (4 specimens measured).

Observed range: Baylei to lower Mutabilis Zones.

Remarks: The variety *longicornuta* occurs in smaller numbers but with a similar frequency to *G. jurassica jurassica*, becoming less common above the mid-Cymodoce Zone.

Genus ***Hystrichosphaeridium*** Deflandre, 1937b emend. Davey & Williams, 1966b.

Hystrichosphaeridium petilum Gitmez, 1970

Plate 2 Fig. 7

Description: Chorate cyst, shell subspherical with the periphragm forming delicate, tubular, distally open processes with 4-6 spines around the mouth. The processes number 15-20 and are about two thirds of the shell length. Length 26-32 μ; breadth 19-25 μ; process length 12.5-19 μ; length of spines at tube mouths ~3 μ. (6 specimens measured.)

Observed range: Baylei to lower Mutabilis Zones.

Remarks: Previous stratigraphic studies (Riding & Thomas, 1988; Thomas & Cox, 1988) have concurred that *H. petilum* is more abundant in the lowest part of the Kimmeridgian. This is expressed in Block 15/21 as presence in the Baylei and Cymodoce Zones and absence in the Eudoxus and younger Zones.

Genus ***Perisseiasphaeridium*** Davey & Williams, 1966b

Perisseiasphaeridium pannosum Davey & Williams, 1966b

Plate 2 Figs. 8, 9

Description: Chorate cyst, shell subspherical to ovoidal bearing two types of processes; 1) broad, distally open, ragged and fenestrate; 2) slender processes which are distally closed or bifurcate. An apical archaeopyle is developed. A slender cingulum divides approximately equal epitract and hypotract. Length (apex lacking) 43-50 μ; breadth 48-56 μ. Length of processes: 1) 28-37.5 μ 2) 19-25 μ.

Observed range: Mid-Mutabilis to Eudoxus Zones.

Remarks: The range base of *P. pannosum* in the mid-Mutabilis Zone is a marker for the base of the *P. pannosum* Subzone of the El Zone. Although, in their revision of Nøhr-Hansen's (1986) zonation, Riding & Thomas (1988) show its range base as base Mutabilis, their range chart (1988, p. 71) shows the first appearance as mid-Mutabilis Zone.

Perisseiasphaeridium ingegerdii Nøhr-Hansen, 1986

Plate 2 Figs. 10, 11

Description: Skolochorate cyst, subspherical central body, with two types of processes; 1) large, hollow, tubiform processes sometimes with supporting roots which give a proximally striated appearance where developed, distally open and often recurved 2) slender, simple processes, distally closed or bifurcate, in the cingular area. An apical archaeopyle is present. Length (apex lacking) 40 μ; breadth 42.5 μ; length of processes 15-25 μ (figured specimen, slide 15/21-25 8270').

Observed range: Mutabilis Zone.

Remarks: The figured specimen does not have such well developed simple processes or supporting roots as the holotype (Nøhr-Hansen, 1986, pl. 3, fig. 11), but is so similar as to represent an extreme of variation. Other specimens (slides 15/21-25 8330' and 8280') are closer to the type material (from Westbury, Wiltshire).

Genus ***Prolixosphaeridium*** Davey *et al.*, 1966 emend. Davey, 1969a

Prolixosphaeridium granulosum (Deflandre) Davey *et al.*, 1966

Plate 2 Figs. 12, 13

Description: Elongate, oval shell with 30-50 tapering undulose, distally closed processes, arranged in rows. The surface of the shell is moderately granulate. An apical archaeopyle is usually present. Overall length 48-51 μ; breadth 27-31 μ; length of processes 8-12.5 μ (10 specimens measured). Fig. 12 (apex lacking); length 37.5 μ, breadth 31 μ, length of processes 9-12.5 μ.

Observed range: Baylei to Eudoxus Zones.

Remarks: *P. parvispinum* is present from Baylei to Mutabilis Zones, and is very similar to *P. granulosum*, but the processes are short and conical, and densely arranged. *Prolixosphaeridium* forms a significant contribution to the assemblage in the Baylei and Cymodoce Zones.

Genus ***Rhynchodiniopsis*** Deflandre, 1935 emend. Sarjeant, 1982b emend. Jan du Chêne *et al.*, 1985b

Rhynchodiniopsis cladophora (Delandre) Below, 1981a

Plate 2 Fig. 14; Plate 3 Figs. 1-3

Description: Cyst outline rounded to pentagonal, with small, blunt apical horn. Cingulum moderately broad, dividing cyst into approximately equal parts - epitract longer on ventral side, hypotract longer on dorsal side. Crests in the form of broad flanges on the sutures giving rise to simple or bifid spinelets, the longest of which occur at the antapex. A precingular archaeopyle is present. Overall length 62.5-130 μ (not including antapical spinelets); breadth 75-94 μ; apical horn 6-12 μ (10 specimens measured).

Observed range: Baylei to top Mutabilis Zone.

Remarks: More abundant in the Baylei and lower Cymodoce Zones.

Genus ***Scriniodinium*** Klement, 1957

Scriniodinium crystallinum (Deflandre) Klement, 1960

Plate 3 Fig. 4

Description: Subspherical to ovoidal theca divided into a longer hypotract and a rounded epitract by a narrow cingulum. The periphragm forms an enclosing membrane which may be folded to give the appearance of a longitudinal furrow to a greater or lesser extent. A precingular archaeopyle is present. Range of overall length 90-98 μ; breadth 71-79 μ; endoblast length 78-84 μ, breadth 58-66 μ (12 specimens measured.

Observed range: Baylei to mid-Mutabilis Zones.

Remarks: The range top of *S. crystallinum* has generally been taken as one marker for the top of the *S. crystallinum* Zone, and the base of the *E. luridum* Zone i.e. the Baylei/Cymodoce boundary (Wollam & Riding, 1983; Nøhr-Hansen, 1986; Riding, 1987; Thomas & Cox, 1987; Riding & Thomas, 1988). However, Cox *et al.* (1987) reported its last occurrence as Mutabilis Zone in Borehole 81/41 (Southern North Sea, U.K. Quadrant 42) and this study substantiates this report. This is a particularly important range extension - consultancy companies invariably date the "γ Shale" as no younger than Baylei Zone due to the presence of *S. crystallinum*.

Genus ***Sirmiodinium*** Alberti, 1961 emend. Warren, 1975

Sirmiodinium grossi Alberti, 1961 emend. Warren, 1975

Plate 3 Fig. 5

Description: The periblast is subcircular to roughly pentagonal in shape, with a blunt apex and flattened antapex. The endoblast is subspherical to ovoidal, with rounded apex and antapex. The distinct cingulum divides the cyst into a larger hypotract and smaller epitract. An apical archaeopyle is sometimes developed. Overall length 55-59.5 μ, breadth 45-55 μ; endoblast length ~50 μ, breadth ~50 μ (4 specimens measured).

Observed range: Cymodoce and Mutabilis Zones.

Genus ***Stephanelytron*** Sarjeant 1961a emend. Stover *et al.*, 1977

Stephanelytron cf. ***scarburghense*** Sarjeant, 1961a emend. Stover *et al.*, 1977

Plate 3 Fig. 7

Description: Shell spherical to ovoidal with a smooth surface bearing tubes arranged in numerous rows, and further irregularly scattered tubes. The tubes are hollow and distally open. The antapex bears a membranous corona; there is an opening (?apical archaeopyle) at the apex. Figured specimen (slide 15/21-25 8403'): length 28 μ, breadth 31 μ, length of tubes ~3 μ.

Observed range: Baylei to Cymodoce Zones.

Remarks: The specimens observed, typified by Pl. 3, Fig. 7, differ from *S. scarburghense* in having a lower corona; Sarjeant (1961a, pl. 15, figs. 12-13, p. 111) quoted a height of 12 μ and a diameter of 28 μ. The range top of *S. scarburghense* in the mid-Mutabilis marks the top of the Ss Subzone and the base of the Pp Subzone of the El Zone (Nøhr-Hansen, 1986; Poulsen, in press). In the studied sections, unfortunately it turned out to be rather scarce.

Genus ***Systematophora*** Klement, 1960

Systematophora areolata Klement, 1960

Plate 3 Fig. 6

Description: Shell spherical to ellipsoidal bearing processes both singular and in groups. The surface of the central body is smooth or has fine grana. The surface is divided into approximately circular areas by distally open, tubular, sometimes furcate or grouped processes, which rise from narrow crests bordering each field. Simple, solid, distally closed or furcate singular processes rise up from the crests and between the field boundaries. An apical archaeopyle is sometimes present. Length 37.5-62.5 μ,breadth 37.5-71 μ, length of processes 25-43 μ (8 specimens measured).

Observed range: Baylei to Mutabilis Zones.

Remarks: Frequent throughout the early to mid-Kimmeridgian.

Genus ***Tubotuberella*** Vozzhennikova, 1967 emend. Brideaux, 1977 emend. Sarjeant, 1982

Tubotuberella apatella (Cookson & Eisenack) Ioannides *et al.*, 1977 emend. Sarjeant, 1982b

Plate 3 Fig. 8

Description: Cavate cyst, endoblast ovoidal to rhomboidal, overall outline rhomboidal. Epitract conical, ending in small truncate horn. Hypotract narrowing distally to a cylindrical to rectangular open protuberance often with folds in the periphragm forming longitudinal projections. Precingular archaeopyle present. Range of overall length 75-87.5 μ, breadth 43.5-50 μ; endoblast length 44-50 μ, breadth 31-37 μ (4 specimens measured). Figured specimen (slide 15/21-25 8043'): apical horn length 5 μ; antapical opening length 19 μ, breadth 19 μ.

Observed range: Baylei to Eudoxus Zones.

Remarks: Occurs sporadically throughout the sequence.

Genus ***Valensiella*** Eisenack, 1963a

Valensiella ovulum (Deflandre) Eisenack 1963a

Description: Shell ovoidal to spherical, surface smooth or granulate, covered by crests fusing to form polygons, the nodes of which are supported by simple or furcate processes. Apical archaeopyle may be present. Length 35.5 μ, breadth 32-47 μ, crests upto 4 μ high (4 specimens measured).

Observed range: Mutabilis and Eudoxus Zones.

Contaminants (see also *Cribroperidinium* sp., p. 86).

In sample 15/21-25 8270', 2 specimens belonging to the *Spiniferites ramosus* group (Ehrenberg, 1838) Loeblich & Loeblich, 1966, were encountered, and are illustrated on Pl. 3, Figs. 9 and 10. The *S. ramosus* group is very common in the Tertiary, and does not range below the Lower Cretaceous. This suggests that either the specimens are caved (this sample is from a cutting), or that the sample has been contaminated by drilling mud or in the laboratory.

PART 3 - REGIONAL MODELLING

7. BIOSTRATIGRAPHIC FRAMEWORK

7.1 AMMONITE ZONATION. (Fig. 3.1)

Faunal provincialism in the ammonites of the Middle and Upper Oxfordian has led to severe problems in correlation and the erection of several schemes of standard ammonite zones. Three provinces are recognised in Laurasia, north of Tethys. The largest and most southerly is the Sub-Mediterranean Province, in which a scheme of ammonite zones and subzones has been worked out based on extensive, continuous sections with faunas consisting mainly of members of the family Perisphinctidae.

The Sub-Boreal Province includes southern England, Normandy, the Boulonnais, northern Germany, parts of Poland and the western U.S.S.R. Despite being a relatively small area, it has, on historical grounds, provided the standard zonal scheme for the Middle and Upper Oxfordian given in the ammonite *Treatise* (Arkell, Kummel and Wright, 1957). This zonation is based on genera of the Perisphinctidae (*Perisphinctes*, *Decipiens* and *Ringsteadia*).

The most northerly province is the much larger Boreal Province, including Scotland, Greenland, Spitsbergen and the Barents Shelf, the Baltic, northern Poland and Russia, northern Siberia, Alaska and Canada. In many parts of the Boreal Province the Perisphinctidae are rare, and the family Cardioceratidae (*Cardioceras, Amoeboceras*) form about 80% of all species and individuals (Sykes & Surlyk, 1976). A revised zonation based on the Cardioceratidae was proposed for the Middle and Upper Oxfordian by Sykes (1975a). The scheme, published in outline in application to northeast Greenland (Sykes & Surlyk, 1976), was refined by Sykes & Callomon (1979) to subzonal level based on detailed stratigraphic work in East Greenland (Surlyk *et al.*, 1973; Sykes & Surlyk, 1976), Scotland (Wright, 1973, Sykes, 1975a, b), and Yorkshire (Wright, 1972), and cored sections in the Wash area of eastern England (Gallois and Cox, 1977).

Middle Oxfordian.

Within the Boreal Province the time-plane corresponding to the base of the Plicatis Zone, which defines the base of the Sub-Boreal/Sub-Mediterranean Middle Oxfordian is readily distinguishable. In the upper part of this zone, the

Cardioceratidae are quite rare (not above 10% of the faunas) whereas in Skye, *Cardioceras* forms 70% of the fauna. This differentiation increases upwards into the Kimmeridgian. The Boreal zonation is therefore based on the evolution of the Cardioceratidae (Sykes & Callomon, 1979). The Middle/Upper Oxfordian boundary is placed between the Tenuiserratum and Glosense Zones, coinciding closely with the transition from *Cardioceras* to *Amoeboceras.*

Densiplicatum Zone: Index - *Cardioceras (Subvertebriceras) densiplicatum* Boden. Divided into :-

Vertebrale Subzone: Index - *Cardioceras (Vertebriceras) vertebrale* (J. Sowerby).

Maltonense Subzone: Index - *Cardioceras (Maltoniceras) maltonense* (Young and Bird).

Tenuiserratum Zone: Index - *Cardioceras (Miticardioceras) tenuiserratum* (Oppel). The Tenuiserratum Zone is defined by the range of the index species. Divided into:-

Tenuiserratum Subzone: Index - as for Zone.

Blakei Subzone: Index - *Cardioceras (Cawtoniceras) blakei* Spath.

Upper Oxfordian

The section at Staffin on the Isle of Skye has been designated the stratotype for most of the zonal scheme (Sykes & Callomon, 1979). The principal faunas of *Amoeboceras* allow the Upper Oxfordian to be divided into four Zones; Glosense, Serratum, Regulare, and Rosenkrantzi (Sykes and Surlyk, 1976). These were subdivided into six Subzones by Sykes and Callomon (1979).

Glosense Zone: Index - *Amoeboceras (Prionodoceras) glosense* (Bigot and Brasil).

The base of the Glosense Zone is indicated by the appearance of *Amoeboceras*. The top of the zone is defined by the upper limit of the range of *A. glosense*. Divided into:-

Ilovaiskii Subzone: Index - *Amoeboceras (Prionodoceras) ilovaiskii* (M.Sokolov)

Glosense Subzone: Index - as for zone.

OXFORDIAN – KIMMERIDGIAN AMMONITE ZONATION

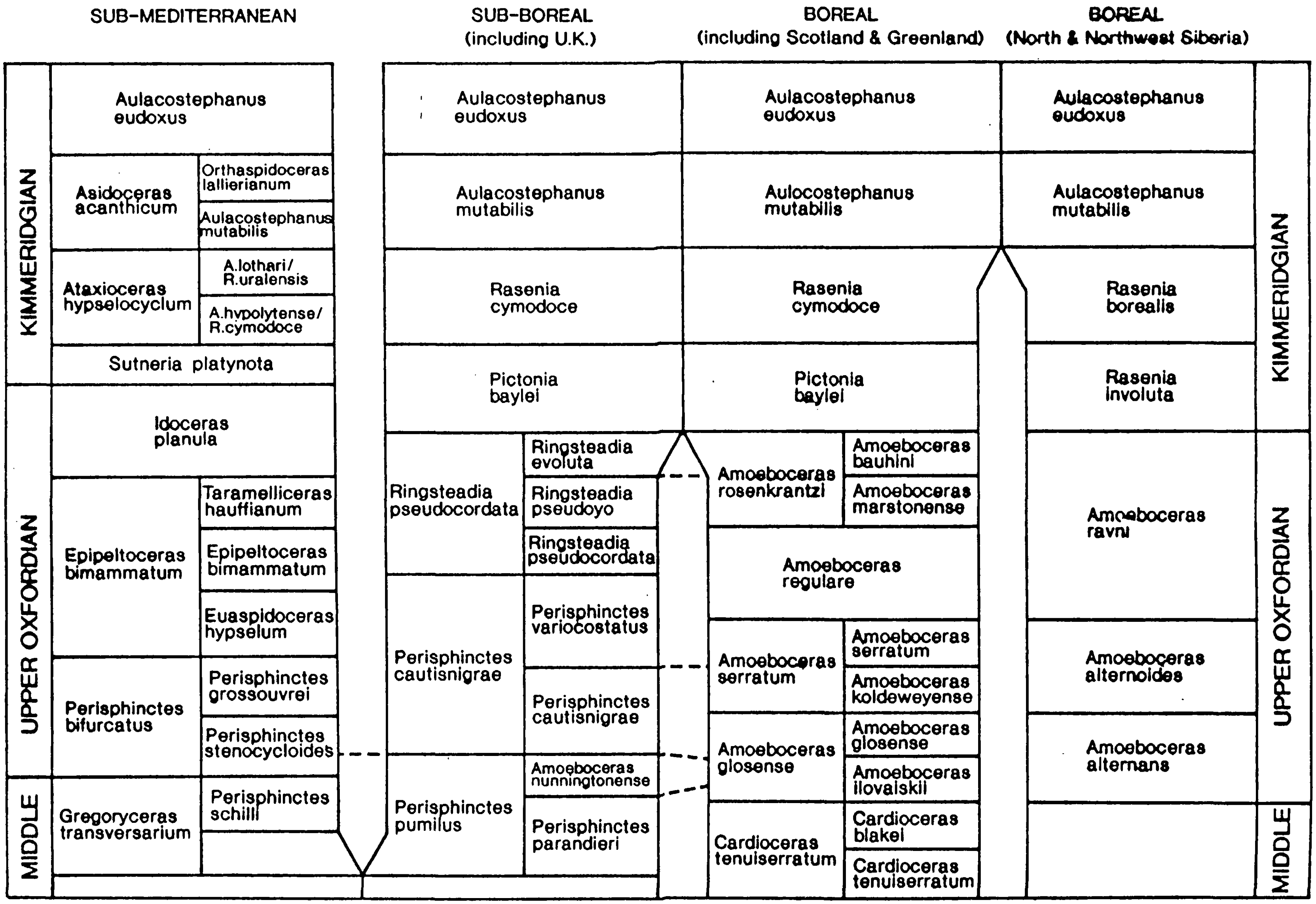


Fig. 3.1. Boreal, Sub-Boreal and Sub-Mediterranean Ammonite Zonation.

Serratum Zone: Index - *Amoeboceras (Prionodoceras) serratum* (J. Sowerby). Defined by the range of the *A. serratum* group - *A. serratum, A. mansoni* Pringle, and *A. koldeweyense* Sykes and Callomon (=*Amoeboceras* sp. nov. Sykes & Surlyk, 1976, p. 424). Divided into:-

Koldeweyense Subzone: Index - *Amoeboceras koldeweyense* Sykes and Callomon

Serratum Subzone: Index - as for zone.

Regulare Zone: Index - *Amoeboceras (Prionodoceras) regulare* Spath. Indicated by the occurrence of the *regulare* group (*A. regulare, A. lecicum* Spath, and *A. shulginae* Mesoznikov) without the *A. serratum* group. The top of the zone is marked by the incoming of *A. rosenkrantzi* Spath.

Rosenkrantzi Zone: Index - *Amoeboceras (Prionodoceras) rosenkrantzi* Spath. Defined by the range of the index species. Divided into:-

Marstonense Subzone: Index - *Amoeboceras (Prionodoceras) marstonense* Spath.

Bauhini Subzone: Index - *Amoeboceras bauhini* (Oppel).

Characterised by the incoming of diminutive species of the *A. bauhini* group (*A. praebauhini* Salfeld and *A. tuberculoalternans* (Nikitin).

The position of *A. bauhini* in relation to the Oxfordian/Kimmeridgian boundary has been redefined (Birkelund & Callomon, 1985) following a temporary exceptional exposure in Skye giving new stratigraphical information. The classification of the top beds of the Staffin Shale Formation has been modified with a redrawing of the boundary. Bed 35 (Sykes & Callomon, 1979, p. 899) contains *Ringsteadia frequens* and *evoluta* in its top 1-2m. Bed 36, a limestone marker, is barren. The lowest 1-15 m of Bed 37 contain *Pictonia densicostata*; *Amoeboceras bauhini* occurs at c.2 and 4-5 m above the base of Bed 37, and the Oxfordian/Kimmeridgian boundary is redrawn at Bed 36 instead of Bed 38. The Bauhini Subzone is largely, if not exactly, equivalent to the Baylei Zone and is entirely Kimmeridgian in age.

Kimmeridgian.

From the base of the Kimmeridgian the Pictoniinae spread northwards and the distinction between Boreal and Sub-Boreal Provinces becomes blurred. The base of the Baylei Zone, (stratotype, Ringstead, Dorset) is used formally to "close" the Boreal Upper Oxfordian by defining the base of the Kimmeridgian Stage at the same level in both Boreal and Sub-Boreal Provinces.

A zonal subdivision of the Lower Kimmeridgian stage *sensu anglico* was proposed by Salfeld (1914) who erected five ammonite Zones; from the base upward:-

Baylei Zone: Index - *Pictonia baylei* Salfeld

Cymodoce Zone: Index - *Rasenia cymodoce* (d'Orbigny)

Mutabilis Zone: Index - *Aulacostephanus mutabilis* (Sowerby)

Yo Zone: Index - *Aulacostephanus yo* (d'Orbigny)

Pseudomutabilis Zone: Index - *Aulacostephanus pseudomutabilis* (de Loriol)

The two highest zones were replaced by Ziegler (1962a) with the Eudoxus and Autissiodorensis Zones respectively - indices: *Aulacostephanus eudoxus* (d'Orbigny) and *Aulacostephanus autissiodorensis* (Cotteau). In the increasingly internationally accepted French terminology, these five Zones (Baylei, Cymodoce, Mutabilis, Eudoxus, Autissiodorensis) comprise the whole of the Kimmeridgian Stage.

Callomon (in Birkelund *et al.*, 1983) has suggested a faunal sequence in the Lower Kimmeridgian *sensu anglico* divided into five successive groups on the basis of Salfeld's zonal classification:-

from below:

1. Forms with perisphinctid ribbing but heavily collared and flared constrictions: *Pictonia* Salfeld (Baylei Zone).

2. Forms still with flared constrictions but developing coarse bullate primary ribbing divided into fasciculate sheaves of secondaries: *Rasenia* Salfeld (Cymodoce Zone).

3. Forms with dense and fine fasciaulate ribbing passing over the venter without weakening: late fine-ribbed *Rasenia* including *Rasenioides* Schindewolf (lower Mutabilis Zone).

4. Forms with dense and fine fasciculate ribbing interrupted on the venter to give a smooth band: early fine-ribbed *Aulacostephanus* Sutner and Pompeckj; including *Aulacostephanoides* Schindewolf (upper Mutabilis Zone).

5. Forms with strong, coarse, straight, non-fasciculate ribbing terminating abruptly on the sharp angular margins of a flat or grooved tabulate venter: *Aulacostephanus* (Eudoxus and Autissiodorensis Zones).

The Cymodoce and Mutabilis Zones are interpreted differently in Britain and France. Salfeld's scheme was erected for a NW European faunal province incorporating NW Germany, the Boulonnais, Normandy, and Britain. In Normandy only the Baylei and Cymodoce Zones are well developed; the most extensive and complete successions are those in Britain, and Birkelund *et al.* (1983) suggest the standard successions be redefined here.

The Cymodoce Zone was commented upon by Birkelund *et al.* (1978). Four *Rasenia* horizons were distinguished in the British Cymodoce Zone; these are, from the base upward:-

I. *Rasenia cymodoce* (d'Orbigny) with *R. (Prorasenia)* cf. *triplicata* (Sowerby) Spath.

II. *Rasenia involuta* Spath and *R. (Eurasenia)* spp.

III. *Rasenia (Zonovia) evoluta* previously referred partly to *R. (Z) uralensis* (d'Orbigny).

IV. *Rasenia (Semirasenia) askepta* Ziegler and associated with *R. (Rasenioides) lepidula* (Oppel).

Several further horizons have been recognised, in eastern England, Normandy and East Greenland. *R. borealis* Spath is from a higher level than *R. orbignyi* Spath (non Tornquist) in Milne Land; and *R. similis* Spath, although thought by Spath to be transitional between *R. cymodoce* and the *R. uralensis* group, may be earlier than either, transitional even between *Pictonia* and *Rasenia* (Birkelund *et* *al.* 1978).

Rasenia inconstans characterises the earliest *Rasenia* bearing horizons in Milne Land (faunas 15 and 16 in Callomon & Birkelund, 1980), followed by a third level of concretions, characterised by *R. cymodoce* (fauna 17). The incoming of this species is taken by both Arkell (1947) and Cox and Gallois (1981) to mark the base of the Cymodoce Zone. In Milne Land, however, this would leave the *R. inconstans* horizons still in the Baylei Zone. A formal definition of the Baylei-Cymodoce Zone boundary is deferred by Birkelund and Callomon (1985) until remaining *Rasenia* faunal sequences (including the South Ferriby section) have been properly worked out.

The Cymodoce-Mutabilis boundary is traditionally put at the level at which "*Rasenia*" changes to "*Aulacostephanus*" (i.e., *Rasenioides* to *Aulacostephanoides*) by the development of a ventral smooth band. Birkelund *et al.* (1978) complied with this interpretation which includes their horizon IV (*R. askepta*) in the Cymodoce Zone. Birkelund *et al.* (1983) propose that the base of the Mutabilis Zone in Britain be drawn at the level at which the "fine-ribbed" Rasenids become dominant, replacing the previously dominant coarse-ribbed *Rasenia* s.s., therefore lowering the boundary. Justification for this lies in the traditional boundary being gradual and hard to recognise, and that *Rasenioides* and *Aulacostephanoides* are successive evolutionary stages of the same lineage, the transition between which is of little significance; it is not "the" transition between *Rasenia* and *Aulacostephanus*. The upper beds of the Cymodoce Zone already contain representatives of the fine-ribbed *Rasenioides*, but they are relatively rare and distinct from *R. evoluta*. It seems therefore that *Rasenioides* and *Rasenia* were following separate evolutionary paths prior to the end of the Cymodoce Zone (Birkelund *et al.*, 1983).

The best biostratigraphical marker for the top of the Mutabilis Zone is the faunal break between predominantly fine-ribbed *Aulacostephanoides* and coarse-ribbed *Aulacostephanus* (indicating the Eudoxus Zone).

No formal subzonal division of the Kimmeridgian applies to NW Europe. However, it appears from a number of richly fossiliferous sequences (including those at Westbury, at Warlingham, and in eastern England) that three faunas can be recognised for the Mutabilis Zone and three for the Cymodoce Zone (Birkelund *et al*, 1978, 1983). With evidence from East Greenland a fourth, lowest fauna in the Cymodoce Zone is recognised. Thus, from the bottom, a *Rasenia inconstans,* *R. cymodoce, R. involuta* and *R. evoluta* faunal subdivision may be tenable, whilst in the Mutabilis Zone the lowest part is characterised by *Rasenioides*, the middle by *A. mutabilis* and *A. eulepidus*, and the highest part by *Aspidoceras*. These subdivisions will be discussed further in relation to the sections investigated.

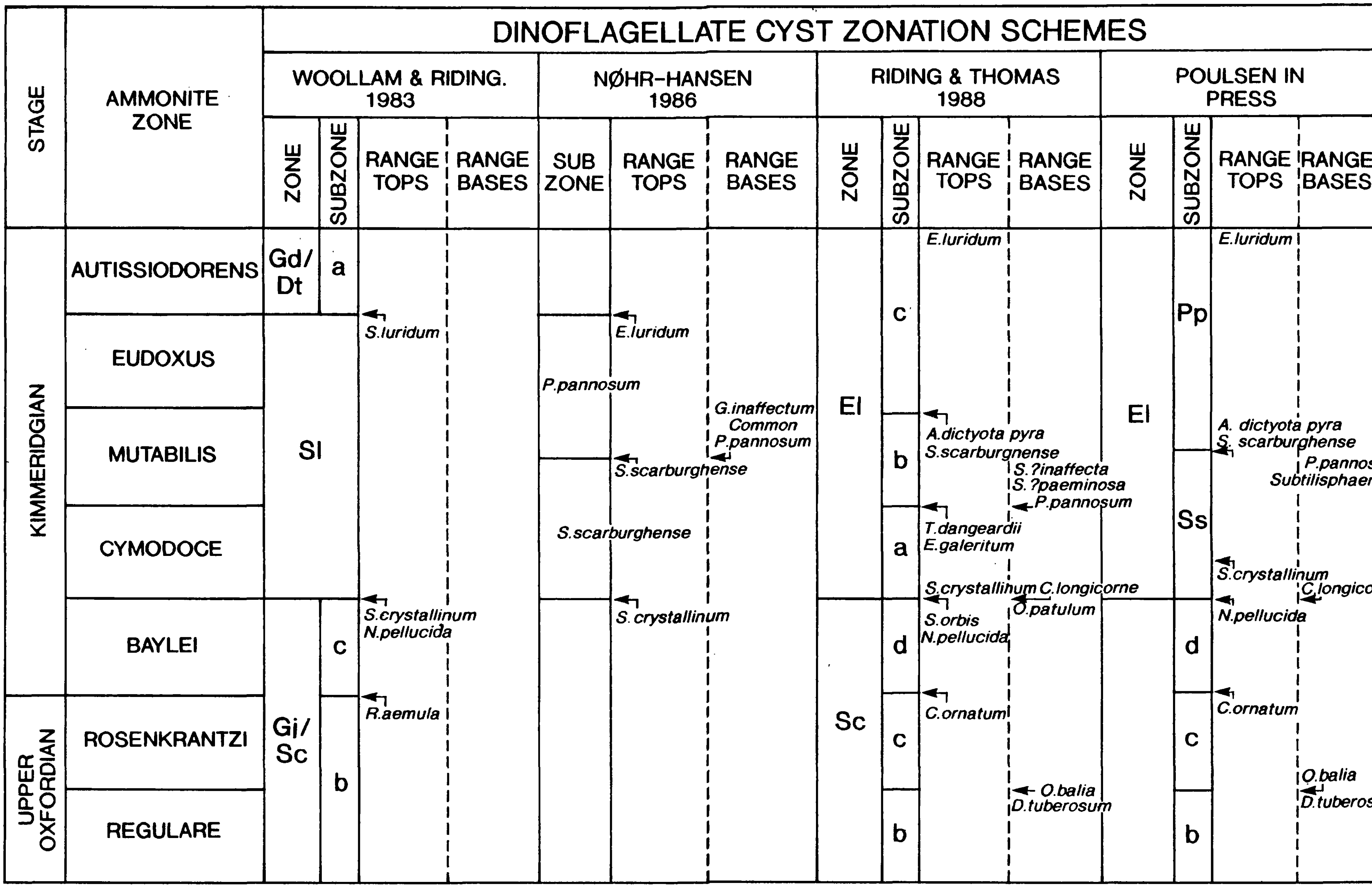
7.2 DINOFLAGELLATE CYST ZONATION

Dinoflagellate cysts (dinocysts) are the most biostratigraphically important palynomorph group in the Upper Jurassic, and several zonal schemes have been erected, notably that of Williams (1977) based on data from Gitmez and Sarjeant (1972) covering the interval Baylei Zone (lowest Kimmeridgian) to Pallasioides Zone (Volgian, or Upper Kimmeridgian *sensu anglico*). Sarjeant (1979) established a dinoflagellate cyst zonation covering Middle to Upper Jurassic on worldwide data (excluding North America).

Woollam and Riding (1983) proposed 18 dinoflagellate cyst assemblage zones covering the interval from latest Triassic to earliest Cretaceous of England. The relevant zones of this scheme relating to the present study are the *Gonyaulacysta jurassica/Scriniodinium crystallinum* Zone (Gj/Sc) covering Mid-Oxfordian to basal Kimmeridgian, and the *Endoscrinium luridum* Zone (El) covering Cymodoce to Eudoxus Zones of the Kimmeridgian. The El Zone was subsequently divided into a lower *Stephanelytron scarburghense* Subzone (Cymodoce to Mid Mutabilis Zone) and an upper *Perisseiasphaeridium pannosum* Subzone (Mid-Mutabilis to Eudoxus Zone) by Nohr-Hansen (1986).

Riding and Thomas (1988) revised the latest Oxfordian to earliest Portlandian (i.e. Mid-Volgian) part of the Woollam and Riding zonation, based on studies of a number of sections on the Dorset coast; their zonal boundaries being based on range bases and/or tops of certain key taxa, measured against lithological sections then correlated with the standard (Boreal) ammonite zones. Riding and Thomas revised the subzones of the El Zone proposed by Nohr-Hansen (1986) to give "Subzone a", equivalent to the Cymodoce Zone, "Subzone b", equivalent to the Mutabilis Zone, and an upper "Subzone c", extending the El Zone up to the top of the Autissiodorensis Zone because the index species, *Endoscrinium luridum*, was reported from this level (Cox *et al.*, 1987). Comparison of these biozonations is given in Fig. 3.2; references for author citations of the dinoflagellate cyst species mentioned may be found in Lentin and Williams (1989).

Fig. 3.2



Comparison of dinoflagellate cyst zonations of the uppermost Oxfordian and Kimmeridgian.

Poulsen (in press) has suggested that Riding & Thomas (1988) were in error in rejecting the subzones proposed by Nohr-Hansen (1986). Their "Subzone a" was defined as the interval from the base of the zone to the range-tops of *Tubotuberella dangeardii* and *Endoscrinium galeritum* and the range bases of *Subtilisphaera inaffecta, Subtilisphaera paeminosa* and *Perisseiasphaeridium pannosum*. However, *T. dangeardii* and *E. galeritum* have both been recorded at younger levels (Woollam & Riding, 1983; Riding, 1987), and the first appearances of the latter three species is reported by Riding & Thomas (1988) as being in the mid-Mutabilis Chronozone, the same as Nohr-Hansen (1986). The top of "Subzone b" is defined as the range-tops of *Aldorfia dictyota* subsp. *pyra* and *Stephanelytron scarburghense*.

Again, as in Nohr-Hansen (1986) the range-tops of these species are recorded by Riding & Thomas (1988) as being in the Mutabilis Chronozone and mid-Mutabilis Chronozone respectively. Riding (1987) reports the last appearance of *A. dictyota pyra* as being in the mid-Mutabilis Chronozone. Thus, it seems that the boundaries between "Subzone a" and "b", and "Subzone b" and "c", are the same, i.e. in the mid-Mutabilis Chronozone. Poulson retains the two subzones proposed by Nohr-Hansen and emends the zone and subzones to extend to the top of the Autissiodorensis Zone (Fig. 3.2).

Scriniodinium crystallinum (Sc) Zone. (Riding & Thomas, 1988.)

Definition - Interval from the range top of *Leisbergia scarburghensis* and the appearance of *Glossodinium dimorphum*, to the extinction of *S. crystallinum*, *Sirmiodiniopsis orbis* and *Nannoceratopsis pellucida* and the range bases of *Cribroperidinium longicorne* and *Oligosphaeridium patulum*.

Age - Oxfordian, base of Tenuiserratum Zone to Early Kimmeridgian, top of Baylei Zone.

Subzone a. Interval from the extinction of *A. senta* (and appearance of *G. dimorphum*) to the extinction of *C. polonicum*.

Age - Oxfordian, base of Tenuiserratum Zone to top of Glosense Zone.

Subzone b. Interval from the extinction of *C. polonicum* to the range-bases *Occisucysta balia* and *Dingodinium tuberosum*.

Age - Late Oxfordian, base of Serratum Zone to top of Regulare Zone.

Subzone c. Interval from the top of Subzone b to the range top of *Ctenidodinium ornatum*.

Age - Latest Oxfordian, Rosenkrantzi Zone.

Subzone d. Interval from the top of Subzone c to the top of the Zone.

Age - Earliest Kimmeridgian, Baylei Zone.

Endoscrinium luridum (El) Zone. (Poulsen, in press.)

Revised definition - Interval from last appearance of *N. pellucida*, last appearance of common *Gonyaulacysta jurassica*, and the first appearance of *Cribroperidinum longicorne*, to the last appearance of *Endoscrinium luridum* and the first appearance of *Egmontodinium polyplacophorum*.

Age: Kimmeridgian, base Cymodoce Chronozone to the top of the Autissiodorensis Chronozone.

Stephanelytron scarburghensis (Ss) Subzone. Revised definition - Interval from the base of the zone to the last appearance of *Aldorfia dictyota* subsp. *pyra* and *Staphanelytron scarburghense*, and the first appearance of *Perisseiasphaeridium pannosum, Subtilisphaera inaffecta, Subtilisphaera paeminosa.*

Age: Cymodoce to mid-Mutabilis Chronozone

Perisseiasphaeridium pannosum (Pp) Subzone. Revised definition - Interval from the top of the Ss Subzone to the top of the Zone.

Age: Mid-Mutabilis to Autissiodorensis Chronozone.

8. RESULTS AND APPLICATION OF THE BIOSTRATIGRAPHIC STUDY.

The age of the Sgiath to Piper Formations is Oxfordian to Kimmeridgian based on both microfossils and macrofossils; the finer details of the dating of the individual members, however, is more clearly understood following detailed study of cored sequences from Blocks 15/21a and 15/22 using ammonite biostratigraphy.

The deposition of the oldest, α Shale Member of the sequence is attributed to transgression in the Late Oxfordian, variously dated as Cautisnigrae (Geostrat Report 052/88) to Pseudocordata Zone (Harker *et al.*, 1987). The succeeding β Sand Member is also believed to be Oxfordian in age. It is from the overlying γ Shale Member that anomalous dates were acquired from ammonites and dinoflagellate cysts. Palynological studies have consistently dated the lower part of the γ Shale Member and underlying β Sand as Late Oxfordian, and the upper part and succeeding δ Sand as earliest Kimmeridgian Baylei Zone in age (Gearhart, Robertson Research and Geostrat Reports). The base of the overlying Kimmeridge Clay Formation has been dated in commercial reports as age equivalent to the upper part of the Mutabilis Zone based again on microfossils, and an unconformity inferred at its base cutting out the Cymodoce Zone.

Within Blocks 15/21a and 15/22 several wells have yielded well preserved though crushed ammonites. Identification of these has allowed more precise definition of the timing of transgressive and tectonic events. Ammonites have most commonly been recovered from the γ Shale, but occasional specimens have also been recovered from the Kimmeridge Clay Formation. This distribution certainly displays sample bias, as far more core material has been obtained from the γ Shale Unit than from any other part of the Upper Jurassic shale sequences. No identifiable ammonites have been recovered from the Marine Shale Unit of the α Shale Member.

8.1 OFFSHORE AMMONITE BIOSTRATIGRAPHY.

Ammonites recovered from 4 wells in the Rob Roy Field are shown in Fig. 3.3 and full faunal lists are given, in downhole sequence, below:-

<u>Well 15/21a-4, Rob Roy</u>

Mutabilis Zone

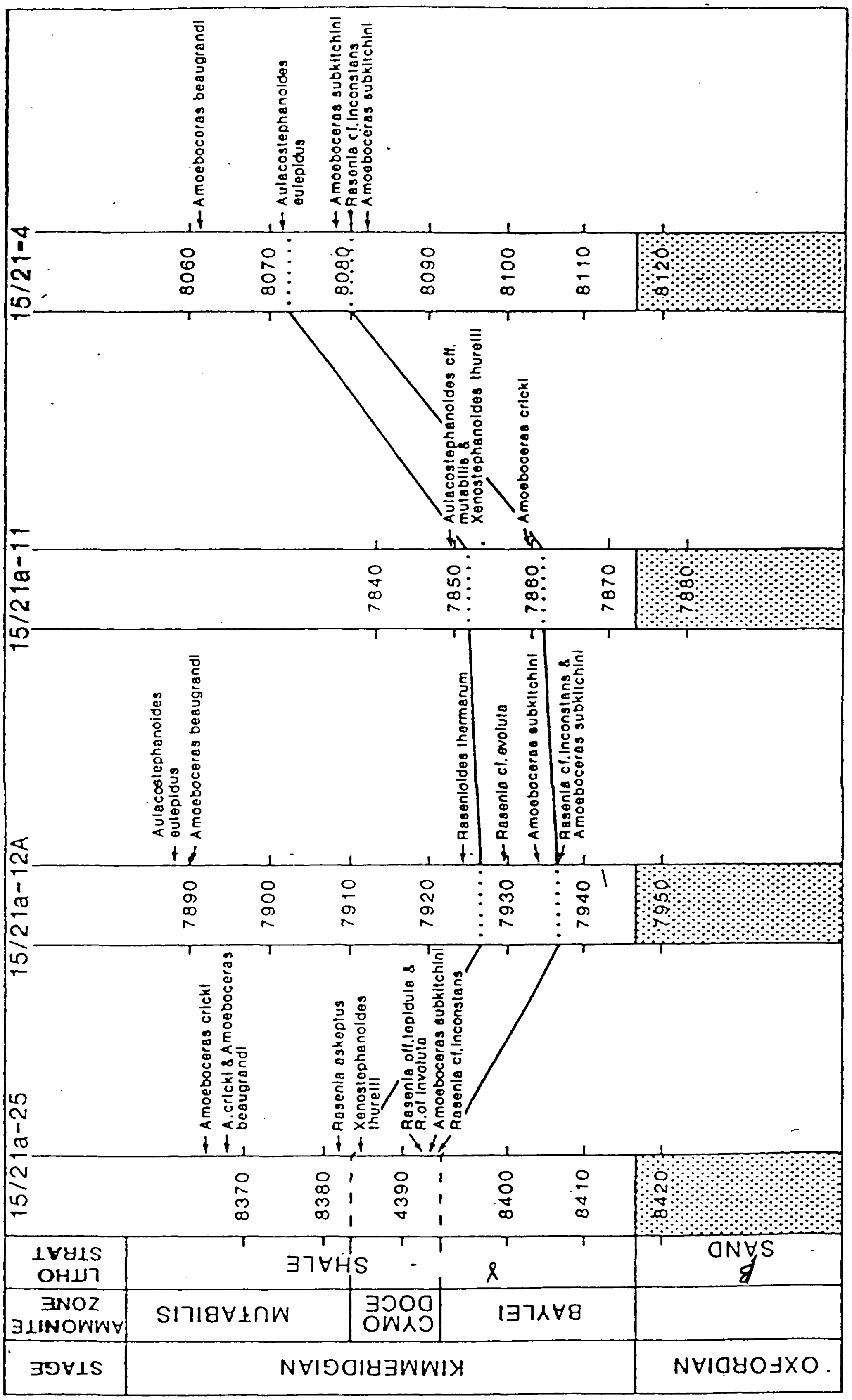


Fig. 3.3. Rob Roy Field Ammonite Zonation and biostratigraphy.

8061'6" - *Amoeboceras (Amoebites)* cf. *beaugrandi* (Sauvage)

8071'6" - *Aulacostephanoides (Aulacostephanites)* cf. *eulepidus* (Schneid)

Lower Cymodoce/Baylei Zone

8079'6" - *Amoeboceras (Amoebites)* cf. *subkitchini* Spath

8080'6" - *Rasenia (Rasenia)* sp. cf. *inconstans* Spath

8081'6" - *Amoeboceras (Amoebites)* cf. *subkitchini* Spath

Well 15/21a-11, Rob Roy

Mutabilis Zone

7850' " - *Aulacostephanoides (Aulacostephanoides)* sp. aff. *mutabilis* (Sowerby);
Aulacostephanus (Xenostephanoides) thurrelli Arkell & Callomon

Cymodoce Zone

7859'6" - *Amoeboceras (Amoebites) cricki* Salfeld (x2)

Well 15/21a-12a, Rob Roy

Mutabilis Zone

7888'3" - *Aulacostephanoides (Aulacostephanites) eulepidus* (Schneid)

7890' - *Amoeboceras (Amoebites) beaugrandi* (Sauvage)

7927'9" - *Rasenia (Rasenioides)* sp. aff. *thermarum* (Oppel)

Cymodoce Zone

7929'7" - *Rasenia evoluta* Spath

7935'5" - *Amoeboceras (Amoebites)* cf. *subkitchini* Spath

Lower Cymodoce/Baylei Zone

7937' - *Amoeboceras (Amoebites)* cf. *subkitchini* Spath;
Rasenia (Rasenia) sp. cf. *inconstans* Spath

Well 15/21a-15, Scott

Baylei Zone

11131'3" - *Amoeboceras (Amoebites) bauhini* (Oppel)

Well 15/21a-25, Rob Roy

Eudoxus Zone (not shown on Fig. 3.3)

8168' - *Aulacostephanus (Aulacostephanoceras)* sp. indet.

8176'5" - *Aulacostephanus* sp. cf. *yo* (D'Orbigny);
Amoeboceras (Euprionoceras) kochi Spath

8176'7" - *Aulacostephanus (Aulacostephanoceras)* cf. *eudoxus* (D'Orbigny);
Aulacostephanoides (Aulacostephanites) eulepidus (Schneid);
Amoeboceras (Euprionoceras) cf. *kochi* Spath

8178'3" - *A. (E.) kochi* Spath

8180'8" - *A. (E.) kochi* Spath

8181'6" - *A. (E.) kochi* Spath

8182'3" - *A. (E.) kochi* Spath

8184' - *Aulacostephanoides (Aulacostephanites) eulepidus* (Schneid);
Amoeboceras (Euprionoceras) kochi Spath

8185'8" - *A. (E.) kochi* Spath

Mutabilis Zone

8377'1" - *Amoeboceras (Amoebites) cricki* Salfeld

8378'5" - *Amoeboceras (Amoebites)* cf. *cricki* Salfeld

8379'2" - *Amoeboceras (Amoebites) beaugrandi* (Sauvage);
Amoeboceras (Amoebites) cf. *cricki* Salfeld

8384' - *Rasenia (Rasenioides) askepta* Ziegler

8385'1" - *Amoeboceras (Amoebites)* sp. indet. (?cf. *A. cricki*)

Lower Mutabilis/upper Cymodoce Zone

8386'4" - *Aulacostephanus (Xenostephanoides)* cf. *thurrelli* Arkell & Callomon

8386'9" - *Aulacostephanus (Xenostephanoides) thurrelli* Arkell & Callomon

Cymodoce Zone

8394' - *Rasenia (Rasenia)* cf. *involuta* Spath (x2)

Lower Cymodoce/Baylei Zone

8394'11"- *Amoeboceras (Amoebites)* cf. *subkitchini* Spath

8395'2" - *Rasenia (Rasenia)* sp. cf. *inconstans* Spath

Well 15/21a-29, Ivanhoe

Lower Mutabilis/Cymodoce Zone

8657'7" - *Amoeboceras (Amoebites)* cf. *cricki* Salfeld

8660'6" - *Rasenia* sp. cf. *coronata* Mesezhnikov

8669'9" - *Amoeboceras (Amoebites)* sp. indet.

8670'8" - *Aulacostephanus (Xenostephanoides)* sp. indet.

8670'9" - *Aulacostephanus (Xenostephanoides)* sp. indet.

Cymodoce Zone

8373'3" - *Amoeboceras (Amoebites)* cf. *kitchini* (Salfeld)

8373'4" - *Rasenia (Rasenia)* cf. *evoluta*

8673'9" - *Amoeboceras (Amoebites)* sp. indet.

Baylei Zone

8675' - *Amoeboceras (Amoebites) bauhini* (Oppel)

Well 15/22-5, Scott.

Mutabilis Zone

14830'6" - *Aulacostephanus (Xenostephanoides)* cf. *lindensis* Arkell & Callomon

14847'6" - *Rasenia (Rasenioides)* cf. *lepidula* (Oppel)

Cymodoce Zone

14854' - *Rasenia (Rasenia)* cf. *evoluta* Spath

14857' - *Rasenia (Rasenia)* cf. *evoluta* Spath

14882'3" - *Rasenia (Rasenia) involuta* Spath

8.2 ONSHORE AMMONITE BIOSTRATIGRAPHY.

Onshore sections were studied to provide control, and also to test the suggestion that a fourfold subdivision of the Cymodoce Zone and threefold subdivision of the Mutabilis Zones may be possible (Birkelund *et al.*, 1978, 1983, and see p.102). The sections examined yielded distinct assemblages which in sections in southern and eastern England have been identified as representative of the top of the Cymodoce Zone (the "Evoluta" Subzone assemblage at Kintradwell), the lower part of the Mutabilis Zone (the "Askepta" Subzone assemblage at Eathie) and the middle part of the Mutabilis Zone (the "Mutabilis" Subzone assemblage at Crackaig Links).

South Ferriby, South Humberside.

The ammonite succession for the relevant part of the South Ferriby succession (ie. time equivalent to the γ Shale *pars.*) is shown in Fig. 2.7. The ammonites collected are sufficient to prove the presence of three zones, the Cymodoce and Baylei Zones of the lower Kimmeridgian, and the topmost zone of the Oxfordian.

Cymodoce Zone; Bed 20 (?19).

The diagnostic forms are *Rasenia* species, though unfortunately poor preservation prevents a specific name being attached to most specimens. Only at one horizon, 2.3 m below the top of the bed, can one be used with any conviction. The specimens here are *Rasenia* cf. *evoluta* Spath which suggests a level high in the Cymodoce Zone, equivalent to Birkelund *et al.*'s (1978) Evoluta horizon, and Callomon & Birkelund's (1980) Fauna 17. This would seem to indicate that almost all the Cymodoce Zone is represented in the section, with a thickness of 3.6 m. If we compare this to typical cored sections in Block 15/21a, where the whole zone appears to be present, we have thicknesses of approximately 2 m (15/21a-4 well) and 2.3 m (15/21a-12a well). This northward thinning may be an extension of variations in thickness due to high subsidence rates in northern Lincolnshire relative to areas adjacent to the Market Weighton block and London Platform, coupled with subsequent erosional events (Riding, 1987). However, it should be noted that the thickness of the Cymodoce Zone is considerably greater in Block 15/22, and on the coast of the Inner Moray Firth.

Baylei Zone, Beds 11-18 (?19).

Diagnostic forms are *Pictonia*, including *Pictonia* sp. cf. *normandiana* Tornquist in the upper part (Bed 18) and *Pictonia* cf. *densicostata* Buckman in the lower part (Bed 14). Also, *Amoeboceras (Amoebites) bauhini* (Oppel) occurs throughout Beds 16 and 14; this species is considered to be diagnostic of the Baylei Zone (Birkelund & Callomon, 1985). In addition, there is (in Bed 14) a horizon with *Prorasenia bowerbanki* Spath. The thickness of the zone is 4.6 m.

Pseudocordata/Rosenkrantzi Zone, Beds 1-10.

The Ampthill Clay beds yield the diagnostic *Ringsteadia*, with *Ringsteadia* cf. *evoluta* in Bed 10 suggesting the topmost subzone of the Pseudocordata Zone. Unfortunately, because there are no *Amoeboceras* specimens present, it is not possible to use the Boreal zonation, which provides a greater degree of accuracy.

Moray Firth, Brora-Helmsdale strip.

The sections studied on the coast of the Inner Moray Firth enforce the concept of a subzonation of the Cymodoce and Mutabilis Zones (Fig. 3.4). Each locality yielded a different assemblage, which demonstrate to a fair extent part of the subdivision of the Cymodoce Zone and Mutabilis Zone by the occurrence of distinct faunas, each fitting into one of the informal subzones in Fig. 3.4, as suggested by Birkelund *et al.*, (1978, 1983). The assemblages are given below in stratigraphic order, from the base upwards, with the subzone of which they are a representative assemblage.

1. Kintradwell - upper Cymodoce Zone, "Evoluta" Subzone.

Aulacostephanus autissiodorensis	
Aulacostephanus eudoxus	
Aulacostephanoides mutabilis	Aspidoceras orthocera
	Aulacostephanoides mutabilis
	Rasenioides askepta
Rasenia cymodoce	Rasenia evoluta
	Rasenia involuta
	Rasenia cymodoce
Pictonia baylei ?	Rasenia inconstans

Fig. 3.4. Informal subdivision of the Cymodoce and Mutabilis Zones.

Rasenia (Rasenia) evoluta Spath

Amoeboceras (Amoebites) rasenense and cf. *rasenense* Spath

Amoeboceras (Amoebites) cricki (Salfeld)

At Westbury, Wiltshire, Birkelund *et al.* (1983) describe the occurrence of *Rasenia involuta* and forms transistional to *R. evoluta* towards the top of the Cymodoce Zone. These are replaced by *Rasenia evoluta* and fine-ribbed *Rasenioides* of the *striolaris-thermarum* group closer to the Cymodoce/Mutabilis boundary. In the basal bed of the Mutabilis Zone, the fauna consists of *Rasenioides askepta*, and *Rasenioides lepidula, R.* cf. *moeschi*, and *R. thermarum*, all very common and providing a clear faunal break to indicate the Mutabilis Zone.

2. Eathie, Cromarty - lower Mutabilis Zone, "Askepta" Subzone.

Rasenia (Rasenia) cf. *evoluta* Spath

Rasenia (Rasenioides) lepidula and cf. *lepidula* (Oppel)

Rasenia (Rasenioides) cf. *moschi* (Oppel)

Rasenia (Rasenioides) askepta and cf. *askepta* Zeigler

Amoeboceras (Amoebites) kitchini and cf. *kitchini* (Salfeld)

Amoeboceras (Amoebites) rasenense Spath

At Westbury, the *Rasenioides* fauna is replaced by *Aulacostephanoides* and *Aulacostephanites* species over about 4 m, and these are very common almost to the top of the Zone, shortly before which they are joined by *Orthaspidoceras orthocera* indicating the "Orthocera" Subzone (Birkelund *et al.*, 1983).

3. Crackaig Links - mid-Mutabilis Zone, "Mutabilis" Subzone.

Aulacostephanoides (Aulacostephanoides) mutabilis and cf. *mutabilis* (Sowerby)

Aulacostephanoides (Aulacostephanites) eulepidus (Schneid)

Aulacostephanoides (Aulacostephanites) cf. *ebrayoides* Arkell & Callomon

Aulacostephanoides (Aulacostephanites) cf. *desmonotus* (Oppel)

Aulacostephanoides (Aulacostephanites) cf. *linealis* (Quenstedt)

Aulacostephanus (Xenostephanoides) cf. *thurrelli* Arkell & Callomon

Amoeboceras (Amoebites) beaugrandi and cf. *beaugrandi* (Sauvage)

Amoeboceras (Amoebites) cf. *rasenense* Spath

Amoeboceras (Amoebites) cf. *kitchini* (Salfeld)

Amoeboceras (Euprionoceras) cf. *kochi* Spath

4. Lothbeg Point - Mutabilis Zone.

Amoeboceras (Amoebites) beaugrandi (Sauvage)

?*Aulacostephanus (Xenostephanoides)* sp.

At Westbury, there is a sharp faunal break at the top of the Mutabilis Zone, where *Aulcostephanoides* and *Aulacostephanites* are completely replaced by *Aulacostephanus* s.s.; there appears to be some overlap in the ranges of these genera around the Wash, where the former two range several metres into the Eudoxus Zone (Gallois & Cox, 1976). The same seems to be true of the Outer Moray Firth, as demonstrated in well 15/21a-25.

5. West Garty - Eudoxus Zone.

Aulacostephanus (Aulacostephanoceras) cf. *eudoxus* (D'Orbigny)

Amoeboceras (Euprionoceras) kochi and cf. *kochi* Spath

The onshore sections examined in the Moray Firth, then, provide us with faunas for the topmost "Subzone" of the Cymodoce zone, the "Evoluta Subzone", and the lowest and middle "Subzones" of the Mutabilis Zone, the "Askepta Subzone" and the "Mutabilis Subzone". At Kintradwell, *Rasenia evoluta* defines a high level in the Cymodoce Zone (Birkelund *et al.*, 1978). At Eathie, although *Rasenia* s.s. persist, species of fine-ribbed Rasenid are dominant, signifying the lowest part of the Mutabilis Zone, the "Askepta Subzone" with *Rasenioides* (Birkelund *et al.*, 1983). At Crackaig Links, the fauna is typified by *Aulacostephanoides mutabilis* and *Aulacostephanites eulepidus*, indicating the middle part of the Mutabilis Zone, the "Mutabilis Subzone" (Birkelund *et al.*, 1983). Lothbeg Point yields an undefinitive Mutabilis Zone fauna, and at West Garty the replacement of *Aulacostephanoides* by *Aulacostephanus* indicates the Eudoxus Zone.

8.3 OFFSHORE CORRELATION USING AMMONITES.

The ammonites recovered from the North Sea wells are often sufficient to correlate the "subzonal" assemblages of the Cymodoce and Mutabilis Zones demonstrated in the Moray Firth coastal succession. In the 15/21a-25 well, the basal part of the Kimmeridge Clay can be identified as earliest Eudoxus Zone age, from the co-existence of *Amoeboceras kochi* and *Aulacostephanites eulepidus*. In the γ Shale Member the Mutabilis and Cymodoce Zones can be identified in 6 of the wells, and the Baylei Zone in 2. Taking "half-way" points (i.e., between younger and older locating taxa) certain observations can be made.

The middle part of the Mutabilis Zone can be proved in 15/21a-4, 15/21a-11, and 15/21a-12a. The oldest part can be identified only in 15/21a-12, 15/21a-25, probably in 15/21a-29, and in 15/22-5. There may be unidentified and/or reduced development of the subzone in 15/21a-4 and 11; however, it appears to be absent, implying a hiatus (Fig. 3.3). The Cymodoce/Mutabilis boundary may be correlated from 7928' in 15/21a-12 to 7852' in 15/21a-11, 8072' in 15/21a-4, 8385'in 15/21a-25, 8675' in 15/21a-29, and 14850' in 15/22-5. The Cymodoce Zone is recognized in all wells except 15/21a-15, and there appears to be little lateral variation in thickness within Block 15/21a, although it is considerably thicker in Block 15/22. The *Rasenia evoluta* and *Rasenia involuta* horizons indicating the top and middle part of the Zone (see p. 101) are both represented, and the *Rasenia inconstans* fauna, in this work considered to represent the oldest Cymodoce fauna, can be recognized in 4 of the wells. The *Rasenia cymodoce* horizon may be missing, due to hiatus, or simply unidentified. The Baylei Zone is proved in 2 wells, 15/21a-29 and 15/21a-15, and its presence can be inferred in the others below the oldest proven Cymodoce sediments.

The ammonite fauna recovered from the wells indicates that the γ Shale Member represents the lower part of the Kimmeridgian, with definitive Baylei, Cymodoce and Mutabilis forms and assemblages. This contradicts the ages of Late Oxfordian to earliest Kimmeridgian (Baylei Zone) attributed to the γ Shale by service companies.

8.4 OFFSHORE DINOFLAGELLATE CYST BIOSTRATIGRAPHY.

Concomitant with the study of the ammonite fauna, samples were prepared for palynological analysis and from these more than 50 taxa of dinoflagellate cysts have been identified, including many of the critical taxa used in the zonation by Riding & Thomas (1988). However, as can be seen in Fig. 3.5, although the scheme can be applied to the wells in 15/21 with confidence, the correlation of the dinocyst zones to the Boreal ammonite zonal sequence in Block 15/21a does not agree in detail with the scheme published by Riding & Thomas (1988) for the Dorset coastal sections.

STAGE	RIDING & THOMAS 1988: AMMONITE ZONE	ZONE	SUB-ZONES	RANGE-TOPS	RANGE-BASES	BLOCK 15/21a: AMMONITE ZONE
LOWER KIMMERIDGIAN	AUTISSIO-DORENSIS	ENDOSCRINIUM LURIDUM (El)	c	E. luridum		
	EUDOXUS					EUDOXUS
	MUTABILIS		b	S. scarburghense A.dictyotapyra		MUTABILIS
	CYMODOCE		a	T.dangeardi E.galeritum	S?inaffecta S?paeminosum P.pannosum	
	BAYLEI	SCRINIODINIUM CRYSTALLINUM (Sc)	d	S.crystallinum S.orbis N.pellucida	C.longicorne O.patulum	CYMODOCE / BAYLEI
UPPER OXFORDIAN	ROSENKRANTZI		c	C.ornatum		
	REGULARE		b		O.balia D.tuberosum	

Fig. 3.5 Comparison of Block 15/21 Ammonite and Dinocyst Zonation with Riding & Thomas (1988).

Core material and cutting samples from 7 wells were examined, 15/22-5 in the Scott Field, 15/21a-11, 12a and 25 from Rob Roy, and 15/21a-16, 18 and 33 from Ivanhoe. The Kimmeridge Clay was examined in detail for palynomorphs in only one well, 15/21a-25, and proved the upper part of the *Endoscrinium luridum* Zone,

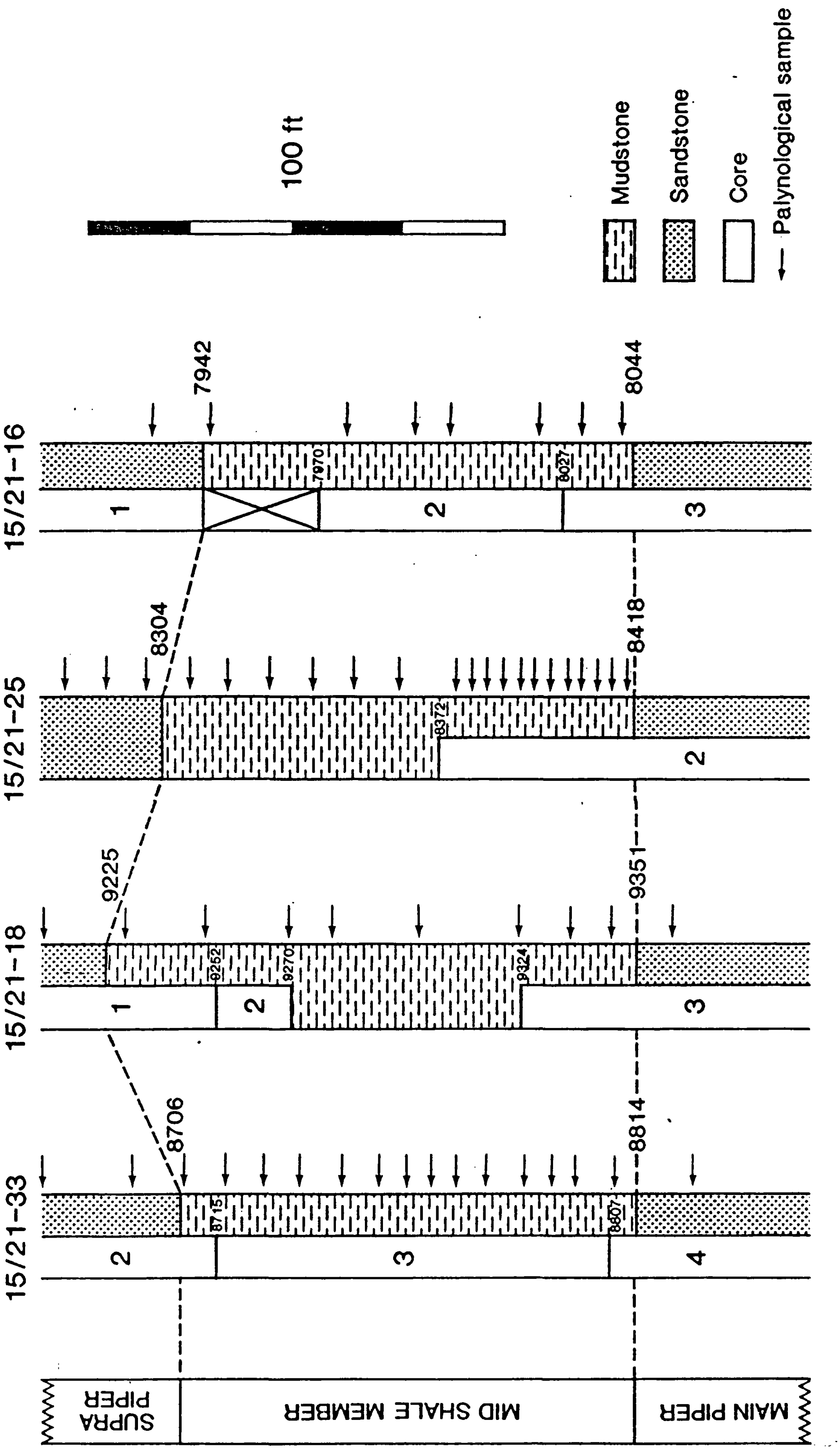


Fig. 3.6. Palynological sample interval in 4 wells.

but as there are no dinozonal boundaries between the upper part of the γ Shale Member and the basal part of the Kimmeridge Clay Formation in this area, the study concentrated on the γ Shale Member. The most detailed studies were carried out on four wells, 15/21a-16, 18, 25, and 33, with entire sections through the γ Shale, and including the sands above and below. Sample distance was not usually greater than 10ft., and was often at 3ft. intervals (Fig. 3.6).

Fig. 3.7 shows the distribution of dinoflagellate cyst taxa in well 15/21a-25 including the records from the Kimmeridge Clay Formation, and Fig. 3.8 is a more complete representation of the ranges and abundances of key dinoflagellate cyst species through the γ Shale Member. As a fairly short stratigraphic sequence was being studied, many species proved to be of limited stratigraphic value. Those species ranging throughout the Oxfordian-Kimmeridgian sequence include *Gonyaulacysta jurassica* subsp. *jurassica* (Deflandre), *Chytroeisphaeridia chytroides* (Sarjeant), *C. mantelli* Gitmez & Sarjeant, *Escharisphaeridia pocockii* (Sarjeant), *Pareodinia ceratophora* Deflandre emend. Gocht, *Ctenidodinium chondrum* Drugg, *Endoscrinium luridum* (Deflandre), *Tubotuberella apatella* Cookson & Eisenack and *Glossodinium dimorphum* Ioannides *et al.*

A number of dinoflagellate cysts are shown to have limited stratigraphic ranges in the wells. These were of considerable value and allowed a number of assemblages to be distinguished. The assemblages can be dated accurately by correlating them to the recovered ammonites. Even where no ammonites have been recovered from a well, we can deduce the age of the shale because dinoflagellate cyst assemblages have been dated using ammonites in nearby wells, and an accurate dinozone chart produced from this data (Fig. 3.8). *Cribroperidinium longicorne* (Downie) has its range-base in the Cymodoce Zone, where the last common *Gonyaulacysta jurassica* subsp. *jurassica* (Deflandre) occur. *Scriniodinium cystallinum* (Deflandre), *Endoscrinium galeritum* (Deflandre) and *Aldorphia dictyota* subsp. *pyra* (Gitmez) all have range-tops in the Mutabilis Zone; for the former two this represents an upward extension of their previously accepted ranges. *Perissiaesphaeridium pannosum* Davey & Williams and *Subtilisphaera* spp.have their range-bases in the Mutabilis Zone, and *Stephanelytron scarburghense* Sarjeant emend. Stover *et al.* tops at the same level.

Dinocyst zonation.

The oldest assemblages recovered, from the β Sand Member, probably belong

RANGE OF OCCURRENCE OF SELECTED DINOFLAGELLATE CYST TAXA RECORDED IN CORES 1 AND 2 OF 15/21a–25 WELL

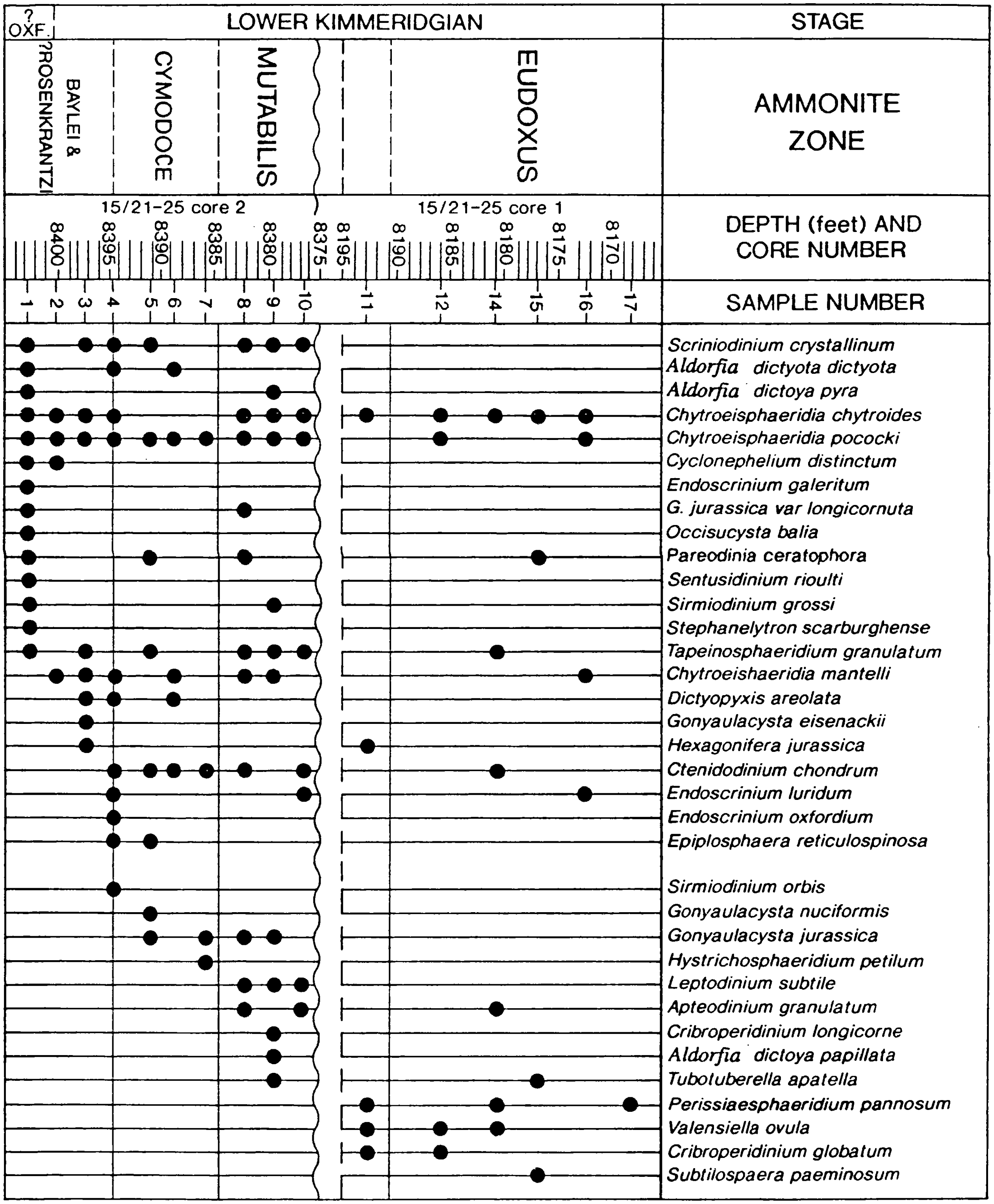


Fig. 3.7. Dinoflagellate cyst range chart for the 15/21a-25 well.

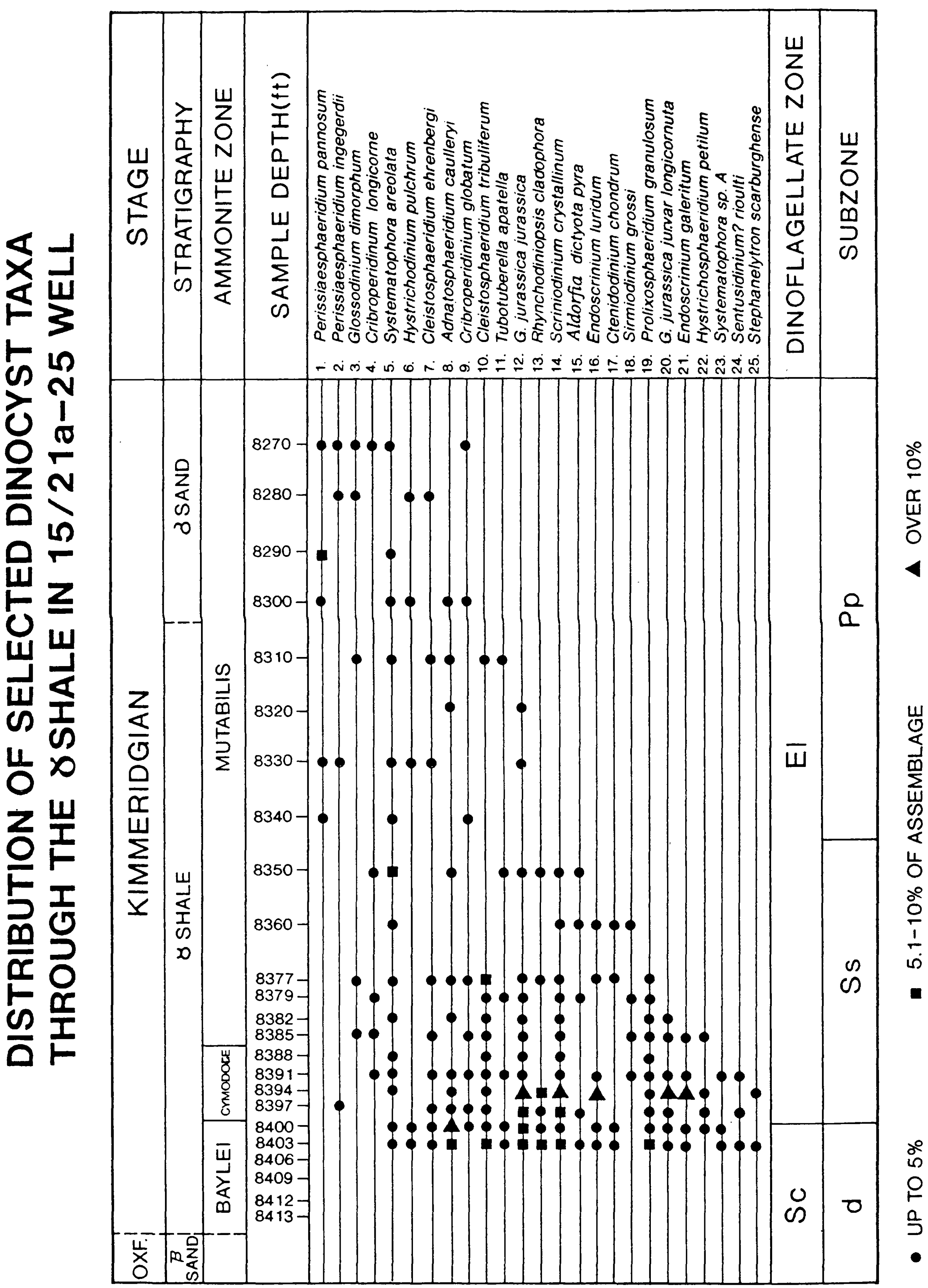


Fig. 3.8. Dinoflagellate cyst range chart through the γ Shale.

to "Subzone c" of the *Scriniodinium crystallinum* (Sc) Zone. This subzone is defined (Riding & Thomas, 1988) as the interval from the range bases of *Occisucysta balia* Gitmez and *Dingodinium tuberosum* (Gitmez) to the range top of *Ctenidodinium ornatum* (Eisenack). The absence of or failure to recognize the latter prevents certain recognition, though as it represents the latest Oxfordian (Rosenkrantzi Zone) its presence can be inferred (see below). "Subzone d" is certainly represented, being the interval from there to the range tops of *S. crystallinum, Sirmiodiniopsis orbis* Drugg and *Nannoceratopsis pellucida* Deflandre emend. Evitt, and the range bases of *C. longicorne* and *Oligosphaeridium patulum* Riding & Thomas, and is equivalent to the Baylei Zone.

The next youngest, *Endoscrinium luridum* (El) Zone includes the rest of the sequence.

The *Stephanelytron scarburghense* (Ss) Subzone is recognized, from the last common occurence of *Gonyaulacysta jurassica* subsp. *jurassica* (Deflandre) and the first appearance of *Cribroperidinium longicorne* (Downie), to the last appearance of *Aldorphia dictyota* subsp. *pyra* (Gitmez). *S. scarburghense* itself is scarce in the samples and does not provide a firm marker. However, the first appearances of *Perisseiasphaeridium pannosum* Davey & Williams and of *Subtilisphaera inaffecta* (Drugg) and *S. paeminosa* (Drugg) also mark the top of the Ss Subzone and the base of the *Perisseiasphaeridium pannosum* (Pp) Subzone. The Ss Subzone is equivalent to the Cymodoce to mid-Mutabilis Zones, and the Pp Subzone includes the rest of the sequence, up to the last appearance of *Endoscrinium luridum* (Deflandre), of mid-Mutabilis to Autissiodorensis Zone age.

Correlation of Dinozones to Ammonite Zones in Blocks 15/21a and 15/22.

Fig. 3.5 shows the anomaly which occurs when the ammonitic ages inferred by Riding & Thomas' (1988) dinozones and Nohr-Hansen's (1986, emended by Poulsen, in press) El Zone are applied to the wells under consideration with strong ammonite control. Poulsen's (in press) rejection of the Riding & Thomas (1988) El Zone subdivision, and emendation of Nøhr-Hansen's (1986) subzones appears to work very well, though this is doubtless partially due to the absence of certain key taxa used by Riding & Thomas (1988) to establish their scheme, including *T. dangeardi, S. inaffecta, D. tuberosum* and *C. ornatum*. However, the range tops of common *G. jurassica jurassica* and *A. dictyota pyra*, and the range bases of *C. longicorne* and *P. pannosum* agree with Poulsen (in press).

Strict ammonite control in the offshore sequences reveals that the range top of *S. crystallinum* is actually within the Mutabilis Zone, not at the top of the Baylei Zone. The last appearance of *S. crystallinum* has previously been reported as Mutabilis Zone by Cox *et al.* (1987), but was subsequently written off as anomalous and possibly the result of contamination of the core by drilling mud impregnation (Thomas & Cox, 1988, p. 324). The range top of *E. galeritum* can be extended up above the top of the Cymodoce Zone, conflicting with the Riding & Thomas (1988) zonation. In this study *E. galeritum* was found as high as the Mutabilis Zone; Woollam & Riding (1983) reported as rare or uncertain its last appearance in the Eudoxus Zone. With the dinoflagellate cyst ranges firmly established within Blocks 15/21a and 15/22 by correlation to positively identified ammonite zones, the dating anomaly of the γ Shale Member can be properly understood, and a thorough critique of the consultancy company datings approached with a full perception of the problem.

Appraisal of service company datings of the γ Shale Member.

Case #1: Gearhart Geoconsultants Ltd. - Biostratigraphic Report on Amoco 15/22-5 well, interval 14640' (sidewall core) to 15120.5' (core).

A threefold palynological division is recognized, the youngest "Unit 1" being approximately equivalent to the δ Sand Member (Fig. 3.9). The palynoflora recovered from 14645' (core) contains *Systematophora* spp., *Sentusidinium* spp., and *Millioudinium* spp., with *G. jurassica* and moderately common *Dingodinium tuberosum* and *Hystrchosphaeridium petilum*. This "unit" is dated as Kimmeridgian, a minor influx of *H. petilum* suggesting an age as old as early Kimmeridgian. "Unit 2" - approximately equivalent to the γ Shale Member, is dated by a rich dinocyst suite (characterised by *G. jurassica, Rhynchodiniopsis cladophora, Systematophora* spp., *Sentusidinium* spp., with accessory numbers of *Leptodinium* spp., *Cleistosphaeridium ehrenbergi/polytrichum, E. luridum, S. crystallinum, C. chondrum* and *Gonyaulacysta eisenacki*) considered to be indicative of a late Oxfordian-early Kimmeridgian age. Minor influxes of *E. luridum* and *S. crystallinum* at 14920.2' (core) and 14950.1' (core) respectively are taken to possibly "reflect a late Oxfordian rather than early Kimmeridgian age". The underlying "Unit 3" (equivalent to the α and β Members) has essentially the same palynological assemblage with *Glossodinium dimorphum* down to 15094.7' (core).

Ammonites recovered from this core clearly show the upper part of the γ Shale

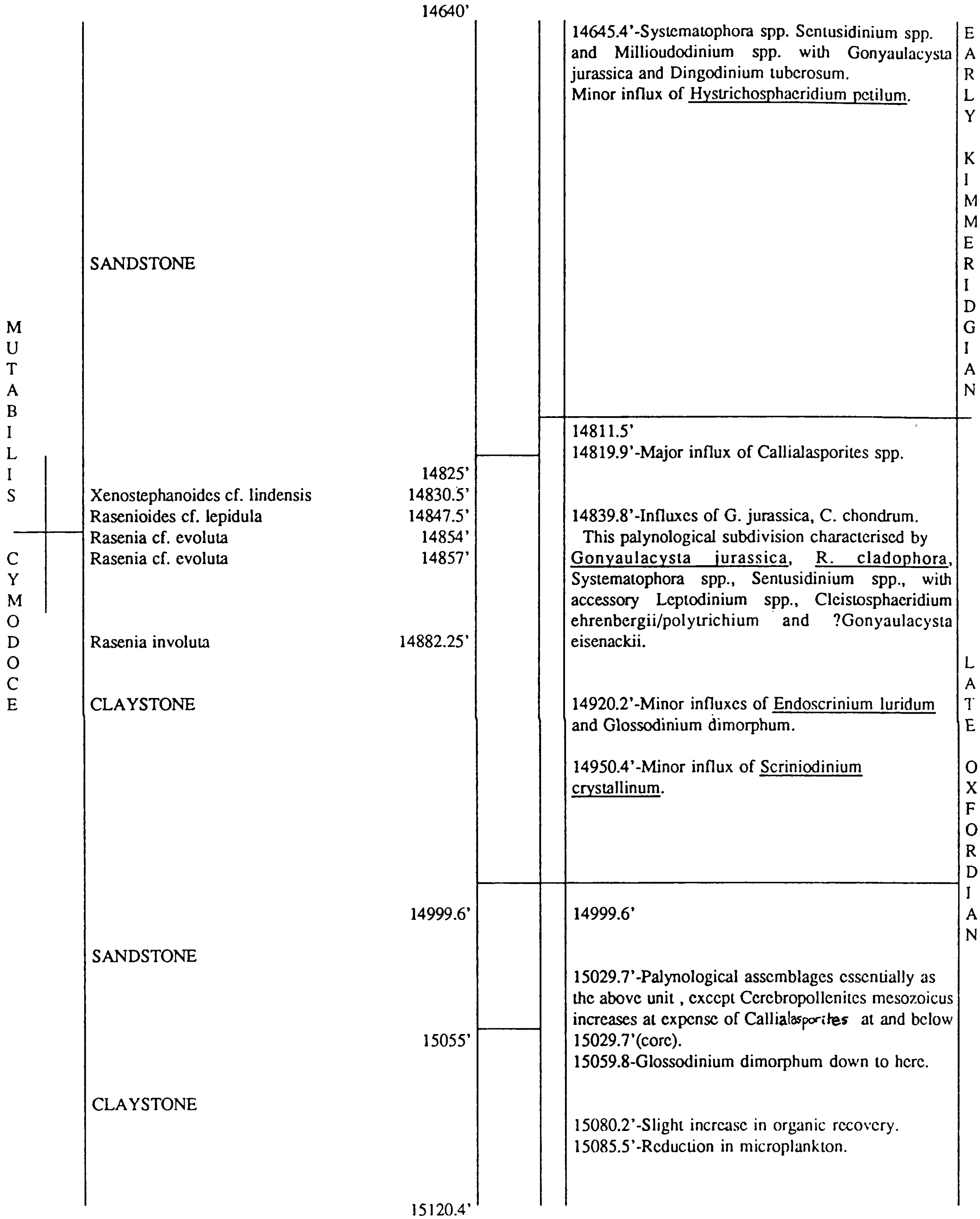


Fig. 3.9 Dinoflagellate cyst and ammonite stratigraphy of the Amoco 15/22-5 well. From data in the biostratigraphic report by Gearhart Geo Consultants Ltd. Underlined species are those upon which ages were based by Gearhart.(Scale 1cm:22')[Left hand side is ammonite dating; right hand side is consultancy analysis].

to be of Cymodoce and lower Mutabilis Zone age. Evidently, the influxes of *E. luridum* and *S. crystallinum* in this well do not reflect a late Oxfordian age, but they may well occur in the earliest Kimmeridgian (Baylei Zone).

Case #2: Robertson Research Biostratigraphic Report on Amerada Hess well 15/21a-11. Interval 7712' (log) to 8272' (log) (Fig. 3.10)
Between 7718' (core) and 7849' (core) (γ Shale) there is the incoming of relatively common *G. jurassica*, with *R. cladophora* becoming common between 7818.6' and 7821' (core). Other elements in this assemblage include *G. dimorphum, Sentusidinium pilosum, Sirmiodinium grossi, Systematophora areolata, Tubotuberella apatella, Chytroeisphaeridia chytroides, Prolixosphaeridium spinosum, E. luridum*, and *C. chondrum* group. The sandy lithology between 7901.5' and 8066.5' (core) (β Sand) yields sparse assemblages, but at 8110.5' (core) there are common chorate cysts, and *G. jurassica, R. cladophora* and *C. chondrum*. At 8206' (swc) abundant dinocysts include *Sentusidinium* spp. and *C.* cf. *chondrum*.

Robertson Research date 7718' (core) as "no younger than" early Kimmeridgian (Baylei Zone) based on the incoming of relatively common *G. jurassica* at 7718', and at 8206' determine that the presence of *C.* cf. *chondrum* indicates an age no older than the Middle Oxfordian, although probably still representing Late Oxfordian deposits. The presence of Cymodoce/Mutabilis ammonites 130 ft. below the incoming of "relatively common" *G. jurassica* would suggest that this criterion has proved inadequate as a marker. However, the author's own observations indicate that the last appearance of common *G. jurassica* is indeed a marker for the lower part of the Cymodoce Zone (Figs. 3.7, 3.8), and I cannot specifically fault the dates attributed by Robertson's on palynological evidence. The only amelioration that seems obvious is some degree of control over use of the loosely applied term "relatively common". *G. jurassica* does, of course, remain common into the Mutabilis Zone, but considering the proportions it may constitute of assemblages older than this, it is a lot less common. This fact does not implicitly prevent *G. jurassica* from still being a relatively common component of the assemblage in comparison with other constituent dinocysts.

Case #3: Robertson Research Biostratigraphical Report on Amerada Hess well 15/21a-12a. Interval 7763' (log) to 8220' (log). (Fig. 3.11)

Ammonite zone	Ammonite dating	Depth	Consultancy analysis
MUTABILIS	SUPRAPIPER UNIT	7712'	7718'-Incoming of common specimens of Gonyaulacysta jurassica. 7718'-7849'-rich and diverse: Glossidinium dimorphum, Senstudinium pilosum, Sirmiodinium grossi, Systematophora areolata, Tubotuberella apatela, Chytroeisphaeridia chytroeides, Prolixosphaeridium spinosum, Leptodinium spp., Endoscrinium luridum, Ctenidodinum chondrum group. 7809.5'-G. jurassica common. 7818.6'-R. cladophora becomes common. 7821' NO YOUNGER THAN BAYLEI ZONE
	Aulacostephanoides sp. aff. mutabilis and Xenostephanoides thurrelli	7856'	7849'
CYMODOCE	Amoeboceras cricki	7859'	
		7871'	
			7901.5' 7901.5'-8066'-sparse (sandy lithology).
	MAIN UNIT		
			8066'
			8110.5'-Rich and diverse, with common chorate cysts, and Gonyaulacysta jurassica, G. cladophora, and Ctenidodinium chondrum.
			8206'-Low diversity of marine elements; Sentusidinium spp., with Pareodinia osmingtonensis rostrata, Ctenidodinium cf. chondrum and Caddasphaera halosa. NO OLDER THAN MIDDLE OXFORDIAN
		8272'	

Fig. 3.10 Dinoflagellate cyst and ammonite stratigraphy of the 15/21a-11 well. From the biostratigraphic report by Robertson Research. Ages based on incoming of relatively common G. jurassica at 7718' (scale 1cm:28') [Ammonite dating on left; consultancy analysis on right].

The core sample at 7775' is dominated by bisaccate pollen grains and undifferentiated chorate dinocysts, with common *G. jurassica* and *R. cladophora*, and *S. crystallinum, C. chondrum* group, *Pareodinia* spp., *Prolixosphaeridium* spp., *G. dimorphum* and *E. luridum*. Core samples at 7819', 7883'8" and 7942' yielded poorly preserved assemblages similar to those above, with, in addition, *T. apatella*. At 7819' (core), *E. galeritum, Esharisphaeridia pocockii* and *Pareodinia borealis* are present. The sample at 8063' (core) yielded *T. apatella* and *S. crystallinum*, the poor assemblage being due to the lithology -the β Sand Member.

Robertson Research date 7775' (core) as "no younger than" early Kimmeridgian (Baylei Zone) due to the presence of *S. crystallinum* and *R. cladophora*. This dating also applies to 7819' and 8063' - these are dated as Late Oxfordian. At 8063' the age probably is Late Oxfordian, within the β Sand Member. However, a Late Oxfordian age for 7819' is incongruous considering that at 70 ft. deeper Mutabilis Zone ammonites occur, and at 120 ft. deeper Cymodoce ammonites occur. As we have seen, both the species used to establish the age of "no younger than" Baylei Zone range well into the Mutabilis Zone, as does *E. galeritum*. Taking this simple factor into account, the palynological information ties in with the ammonite evidence with much less disparity.

Case #4: Geostrat Biostratigraphic Report on Amerada Hess well 15/21a-25. Interval 7950' to 8790' (log). (Fig. 3.12)

Interval 8090'-8193' (log and corrected core). Kimmeridge Clay Formation. Geostrat base the top and age of this interval on the top ranges of *S. luridum, S. paeminosum* and prominent *P. pannosum* at 8090'. The top ranges of the former two indicate penetration of Geostrat's LJP8a subzone (equivalent to the Autissiodorensis Zone and the top half of the Eudoxus Zone). This is supported by prominent *P. pannosum* and the top occurrence of *Aptodinium* cf. *prostratum*, and the range top of *G. jurassica* at 8140'. The top of LJP8b subzone (equivalent to the bottom half of the Eudoxus and the Mutabilis Zones) is indicated at 8160' by common *S. paeminosum* and the range base of prominent *P. pannosum*, with the range base of *S. paeminosum* at 8175' suggesting an age no older than upper Mutabilis Zone, and *C.* cf. *longicorne* at 8190' confirming a Mutabilis age. The ammonite evidence for this core indicates a basal Eudoxus Zone age for the oldest Kimmeridge Clay Formation sediments present; quite why *C.* cf. *longicorne* should confirm a Mutabilis Zone age is an enigma, but disregarding this, there is no

Zone	Ammonite dating	Depth	Consultancy analysis
		7763'	7775'-Gonyaulacysta jurassica, R. cladophora, Scriniodinium crystallinum; with Ctenidodinium chondrum gp., Pareodinia spp., Prolixosphaeridium spp., Glossodinium dimorphum, Endoscrinium luridum. NO YOUNGER THAN BAYLEI ZONE
	SUPRAPIPER UNIT		7819'-Endoscrinium galeritum, Escharisphaeridia pocockii, and Pareodinia borealis. Also, in common with 7883'8" and 7942', G. jurassica, R. cladophora, Tubotuberella apatela, Ctenidodinium chondrum, Scriniodinium crystallinuium, E. luridum. LATE OXFORDIAN 7883'8"
MUTABILIS	Aulacostephanoides eulipidus	7888'3"	
	Amoeboceras beaugrandi	7890'	
	Rasenioides sp. aff. thermarum	7927'10"	7942'-Ostracods: Galliaecytheridea postrotunda.
	Rasenia evoluta	7929'7"	7947' Vernoniella.
CYMODOCE	Amoeboceras subkitchini	7935'5"	7952'-Agglutinant-dominated microfaunas.
	Amoeboceras subkitchini & Rasenia cf. inconstans	7937'	
	MAIN UNIT		8020'10"-Barren; Main Piper Sandstone.
			8063'-Scriniodinium crystallinum. LATE OXFORDIAN
			8165'-Ctenidodinium chondrum.
			8187'-C. chondrum.
		8220'	

Fig. 3.11 Dinoflagelate and ammonite cyst stratigraphy of the 15/21a-12 well. From Robertson Research. Age based on appearance of G. jurassica, G. cladophora, S. crystallinum at 7775' by Robertson Research.(Scale 1cm:22') [Ammonite dating on left; consultancy analysis on right].

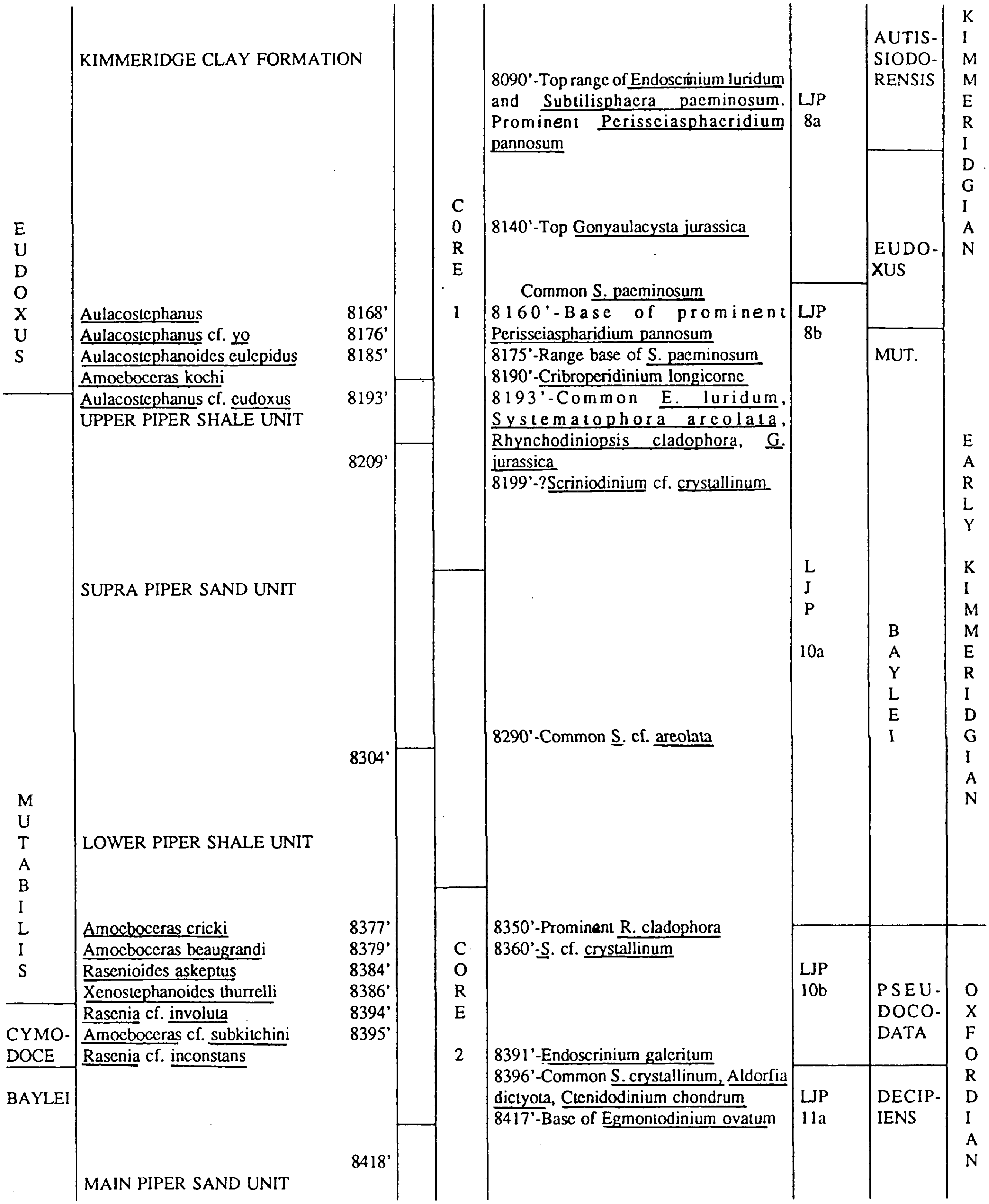


Fig. 3.12 Dinoflagellate cyst and ammonite stratigraphy of well 15/21a-25. From data in the biostratigraphic report by Geostrat Ltd. Ages based on dinocyst events on right hand side of column by Geostrat Ltd (scale 1cm:17') [Ammonite datings on left].

anomaly thus far.

Geostrat now infer an unconformity at the base of the Kimmeridge Clay Formation from the "absence of Cymodoce age sediments", marking the sequence boundary with the highly transgressive Kimmeridge Clay Formation onlapping the underlying Piper Formation.

Interval 8193'-8350' (corrected core and log). "Upper Piper Shale Unit" (=Transgressive Unit), δ Sand Member, and γ Shale Member (*pars.*). 8193' yielded common *E. luridum*, several *R. cladophora* and *G. jurassica* which is implied as having an early Kimmeridgian (Baylei Zone) age, with subsequent prominent *S.* cf. *areolata*, an increase in *R. cladophora* at 8196' and ?*S.* cf. *crystallinum* at 8199' confirming a Baylei Zone age. Ammonites from deeper in the core indicate that all of this interval is within the Mutabilis Zone, which means that an unconformity at the top would be cutting out upper Mutabilis Zone sediments. The range chart for well 15/21a-25 (Fig. 3.8) shows that all the dinocysts mentioned in the Geostrat assessment of the age of this interval remain common well into the Mutabilis Zone. The report makes note of common *S.* cf. *areolata* at 8290'as a significant palynofloral event normally associated with the base of the δ Sand Member; this work can add nothing to this observation.

Interval 8350'-8776' (log). γ Shale Member (*pars.*), β Sand Member and α Shale Member (*pars.*). The top and age of this interval are based on prominent *R. cladophora* and several *S.* cf. *crystallinum* at 8350', taken to indicate penetration of Geostrat's LJP10b subzone (equivalent to the Pseudocordata Zone), which they confirm by common *S. crystallinum* morphotypes at 8360' and *E. galeritum* at 8391'. Ammonites from this interval indicate a Mutabilis Zone age between 8377' and 8386', and once again, *S. crystallinum* and *E. galeritum* are invoked to infer an older age than they necessarily represent. *S.crystallinum* is common at 8396' and is associated with *Aldorfia dictyota* and *C. chondrum*. Geostrat use the latter to indicate penetration of the LJP11a subzone (equivalent to the Decipiens Zone); the ammonites recovered from 8394' and 8395' indicate a Cymodoce Zone age, which is in no way disparaging of the palynological evidence when the revised ranges are taken into account.

In conclusion, the identification of ammonites has allowed precise ages to be assigned to the constituent members of the sequence, and to two of the three major transgressive events seen in the Upper Jurassic in Block 15/21. No ammonites have been recovered from the first transgressive event represented by the Marine Unit of the α Shale Member at the base of the sequence, but the γ Shale transgression has been demonstrated to be basal Kimmeridgian in age. The ammonite fauna recovered from Rob Roy wells indicates that γ Shale deposition continued at least until mid-Mutabilis Zone times, with the δ Sand being of mid- to upper Mutabilis Zone age. Ammonites recovered from the basal part of the Kimmeridge Clay Formation in the 15/21a-25 well indicate an earliest Eudoxus Zone age for the final transgressive pulse that terminated δ Sand deposition and heralded the onset of Kimmeridge Clay deposition.

9. DISCUSSION AND CONCLUSIONS.

9.1 CORRELATION OF THE SGIATH/PIPER INTERVAL IN THE WITCH GROUND GRABEN.

Harker *et al.* (1987) erected the Sgiath Formation as the deltaic to shallow marine sands and carbonaceous mudstones and coals which they interpreted as representing the widespread Mid-Oxfordian transgression (Rawson & Riley, 1982; Turner *et al.*, 1984). In this study it is considered that the Sgiath sediments are likely to be entirely Late Oxfordian in age. The Sgiath was defined as encompassing the pre-"I Shale" Piper Units (Maher, 1980; Turner *et al.*, 1984) overlying paralic Pentland Formation sediments in the Piper Type well (15/17-4). In the type well of the Sgiath Formation, 14/19-4, it was previously designated as Pentland Formation by Turner *et al.* (1984).

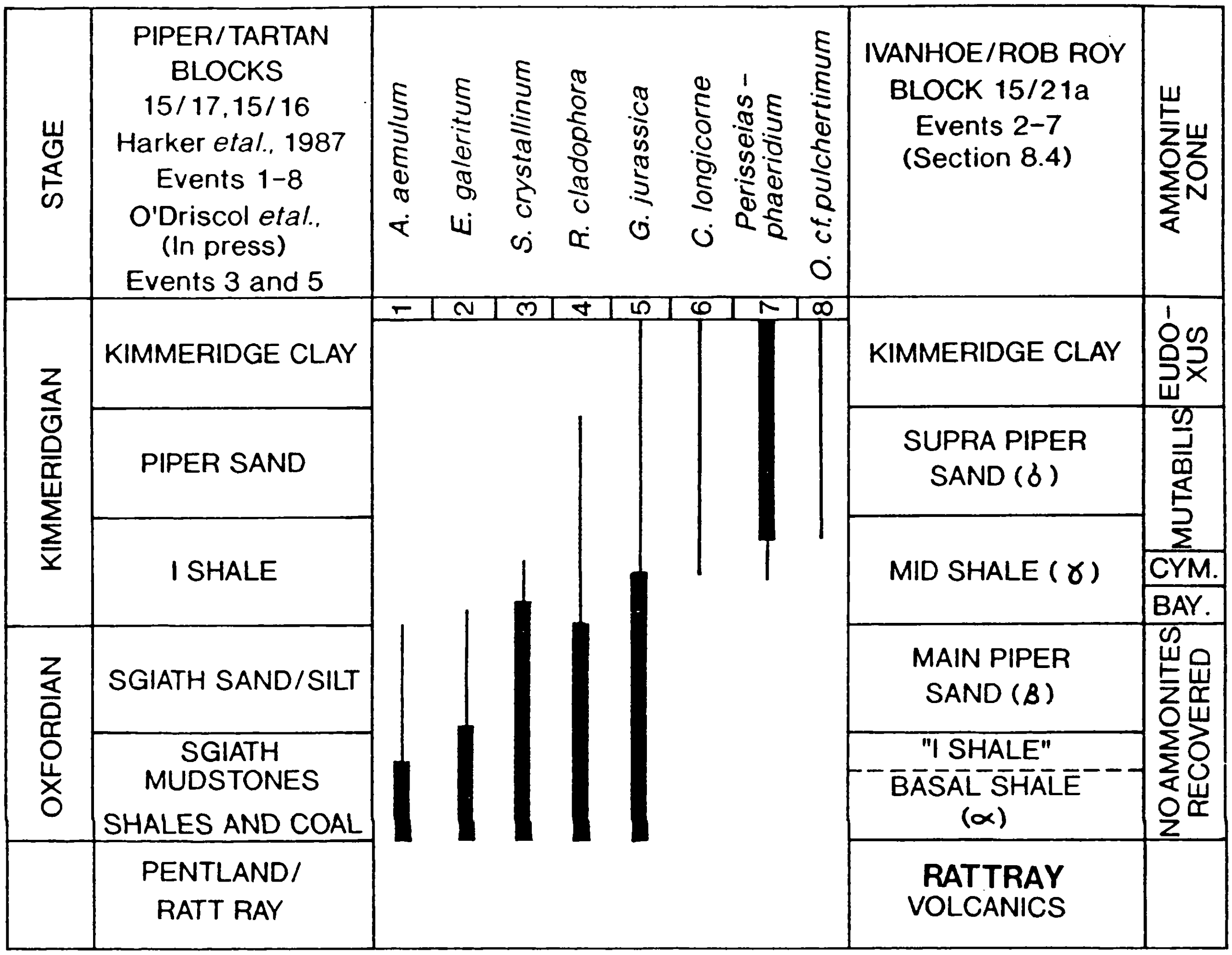
To demonstrate the correlation of the Sgiath and Piper sequences in the Witch Ground Graben, it is essential to be able to identify the "I Shale" as defined in its type well (15/17-4) by Maher (1980).

Biostratigraphic Considerations.

Palaeontological work on core from wells in Blocks 14/19 and 15/17 confirmed the local correlation of the Sgiath Formation (Harker *et al.*, 1987, fig. 8). The Sgiath Formation was identified by a dinocyst assemblage of *Adnatosphaeridium aemulum, Endoscrinium galeritum, Scriniodinium crystallinum, Rh nchodiniopsis cladophora* and *Gonyaulacysta jurassica.* In the basal Piper Formation "I Shale", *A. aemulum* and *E. galeritum* were lacking; *S. crystallinum, R. cladophora* and *G. jurassica* became less common, and were joined by *Cribroperidinium longicorne, Perisseiasphaeridium* sp. A and *Oligosphaeridium* cf. *pulchrum*, along with *Rasenia* ammonites (Cymodoce Zone) (Fig. 3.13).

O'Driscoll *et al.* (in press) traced the "I Shale" into the Tartan Field (southern part of Block 15/16) using a marked downhole increase in *Gonyaulacysta jurassica* and the top occurrence of *Scriniodinium crystallinum* (which incidentally they mark as intra-Cymodoce Zone in age), and attribute a Cymodoce-Mutabilis Zone age to it.

In the Piper Field, Maher (1980) originally dated the "I Shale" as Decipiens Zone at the bottom, and Pseudocordata Zone at the top. These dates have been



Dinoflagellate cyst events 1-8 were used by Harker etal., 1987 to correlate the Sgiath and Piper formations in Blocks 14/19 (Type Sgiath) and 15/17 (Type Piper). O'Driscoll etal., correlated the I shale into Block 15/16 (Tartan Field) using events 3 and 5. Events 2-7 are seen to occur in the γ shale (="Mid Shale") in Block 15/21, evidence for this being equivalent to the I shale, rather than the marine unit of the α shale (="Basal shale") which displays a late Oxfordian assemblage.

Fig. 3.13. Dinocyst correlation in the Witch Ground Graben.

doubted (Riley, pers. comm.) but have encouraged consultancies to correlate the "I Shale" with the upper, marine part of the α Shale in Block 15/21 on biostratigraphic evidence, as the marine part of the α Shale has a characteristically Late Oxfordian assemblage of dinocysts and foraminifera. The correlations have been further complicated by the insistence of the consultancy companies that *Scriniodinium crystallinum* tops in the basal Kimmeridgian Baylei Zone, and that *Endoscrinium galeritum* tops in the Cymodoce Zone. The reasons for this are quite clear; all dinoflagellate Late Jurassic range standards have been developed from onshore sections, where they seem to be reasonably accurate. No detailed offshore comparative biostratigraphic study of dinoflagellate cysts has previously been carried out with *in situ* (offshore) ammonite data to serve as a control.

As the biostratigraphic evidence resulting from this study, presented in the previous chapter, conclusively demonstrates, the "I Shale" has been correctly correlated from the Piper Field into the Tartan Field by O'Driscoll *et al.* (in press). This same shale correlates with the γ Shale in Block 15/21, and not with the α Shale. The Late Oxfordian α Shale is clearly to be included in the Sgiath Formation, the basal shale of the Piper Formation, the "I" or γ Shale, being of Kimmeridgian (Baylei-Mutabilis Zone) age.

Log Character Considerations.

The top of the Sgiath Formation and base of the overlying Piper Formation is defined by the change in log character from low-gamma-ray sands to higher-gamma-ray mudstones of the marine "I Shale" (Harker *et al.*, 1987, p. 812). The lower two units of the α Shale were therefore assigned to the Sgiath Formation in Block 15/21 as they represent non-marine sedimentation, with the Marine Shale Unit correlated to the "I Shale".

Boote & Gustav (1986, fig. 9) also favoured this correlation, though their interpretation is now considered incorrect (Harker, pers. comm.). O'Driscoll *et al.* (in press) from their correlations considered the type and reference wells used for the Sgiath Formation to contain condensed sequences, with fully marine sands and shale sequences developed below the "I Shale" in the south of Block 15/17, and in Block 15/21. Here, it is the first marine shale of the Sgiath Formation which has been correlated, by a change to a higher-gamma-ray signal on logs, to the "I Shale".

Thus, in Block 15/21, the α Shale and β Sand can be assigned to the Sgiath Formation; and the γ Shale, δ Sand and Transgressive Unit can be assigned to the Piper Formation.

The units are herein redefined for Block 15/21 and assigned to their correct Formations, from below:-

The Sgiath Formation (Harker *et al.*, 1987);

the Basal Sgiath Shale Member, in which a Coal Unit, a Paralic Unit and a Marine Unit can readily be recognized;

the Sgiath Sand Member;

The Piper Formation (Deegan & Scull, 1977);

the Piper I Shale Member;

the Piper Sand Member, divided into a Sandstone Unit, and a Transgressive Unit at the top.

Thus, the Sgiath Formation is entirely of Late Oxfordian age. The base Piper Formation I Shale represents the basal Kimmeridgian transgression (Rawson & Riley, 1982), deposition continuing until mid-Mutabilis Zone times, with Piper Formation deposition finally being terminated by the base Eudoxus transgression (Harker *et al.*, 1987) (Fig. 3.14).

9.2 JURASSIC TECTONICS AND SEDIMENTATION IN BLOCK 15/21: *MODUS OPERANDI* AND TIMING.

The Rattray Volcanics and Pentland Formation sedimentary sequence of the Fladen Group were deposited during extensional rifting associated with collapse of the Central North Sea Dome in the course of the Mid-Cimmerian tectonic event (Eynon, 1981). An isochore map of this sequence in the Outer Moray Firth (Fig. 3.15) exhibits a strong north-south arrangement, which is attributed to control by north-south and northeast-southwest faults. These faults are termed the "Viking" Trend faults as they parallel the faults that control the Viking Graben to the east (Boldy & Brealey, in press). The isochore map also demonstrates the Middle Jurassic Fladen Groups absence in the western part of the Outer Moray Firth, and to the east, where Zechstein deposits are overstepped, onlapping the Fladen Ground Spur. It seems probable that a similar north-south fault block extended through quadrant 14, the relationship having been obscured by later tectonic events.

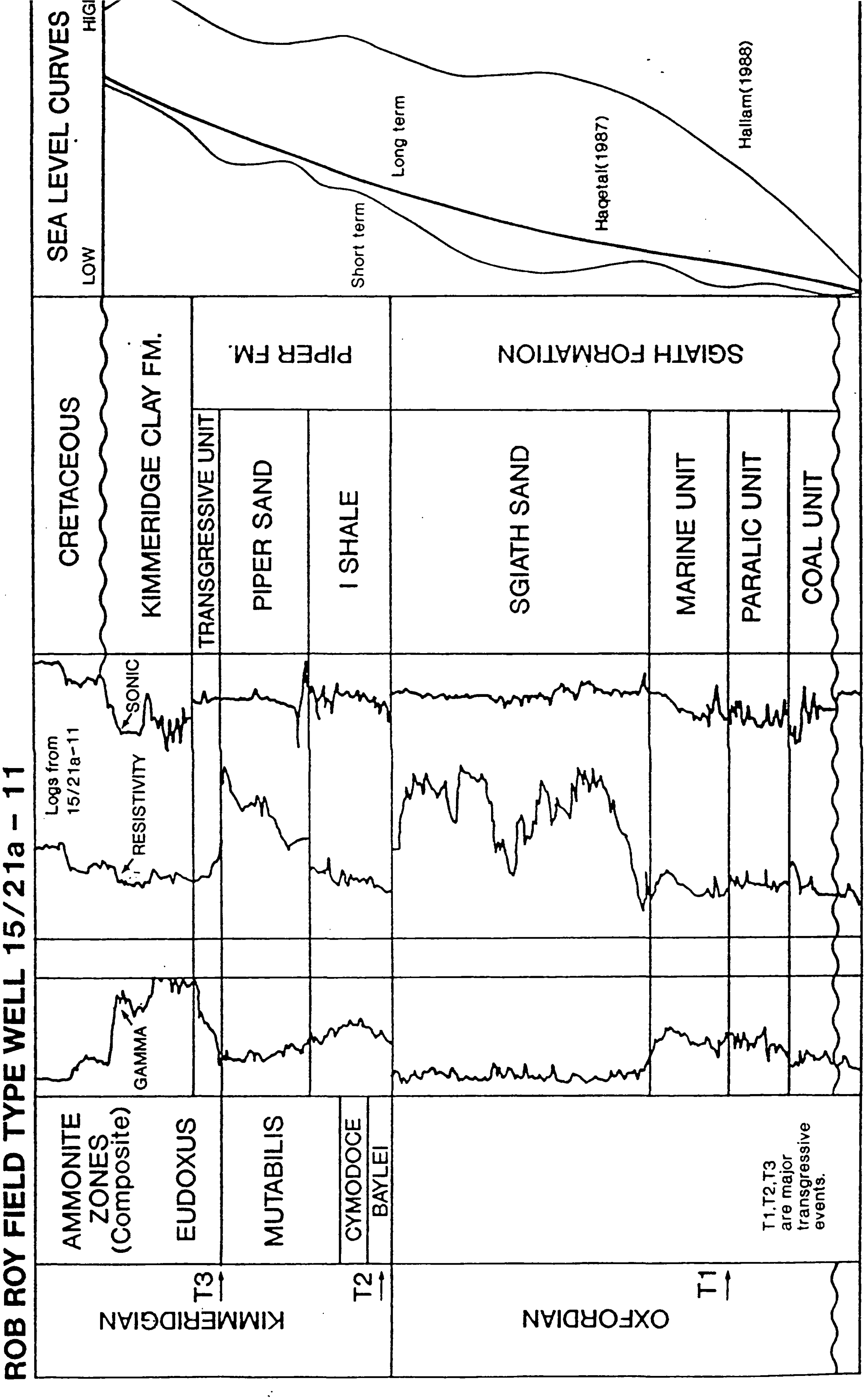


Fig. 3.14. Late Oxfordian to Kimmeridgian transgressive events.

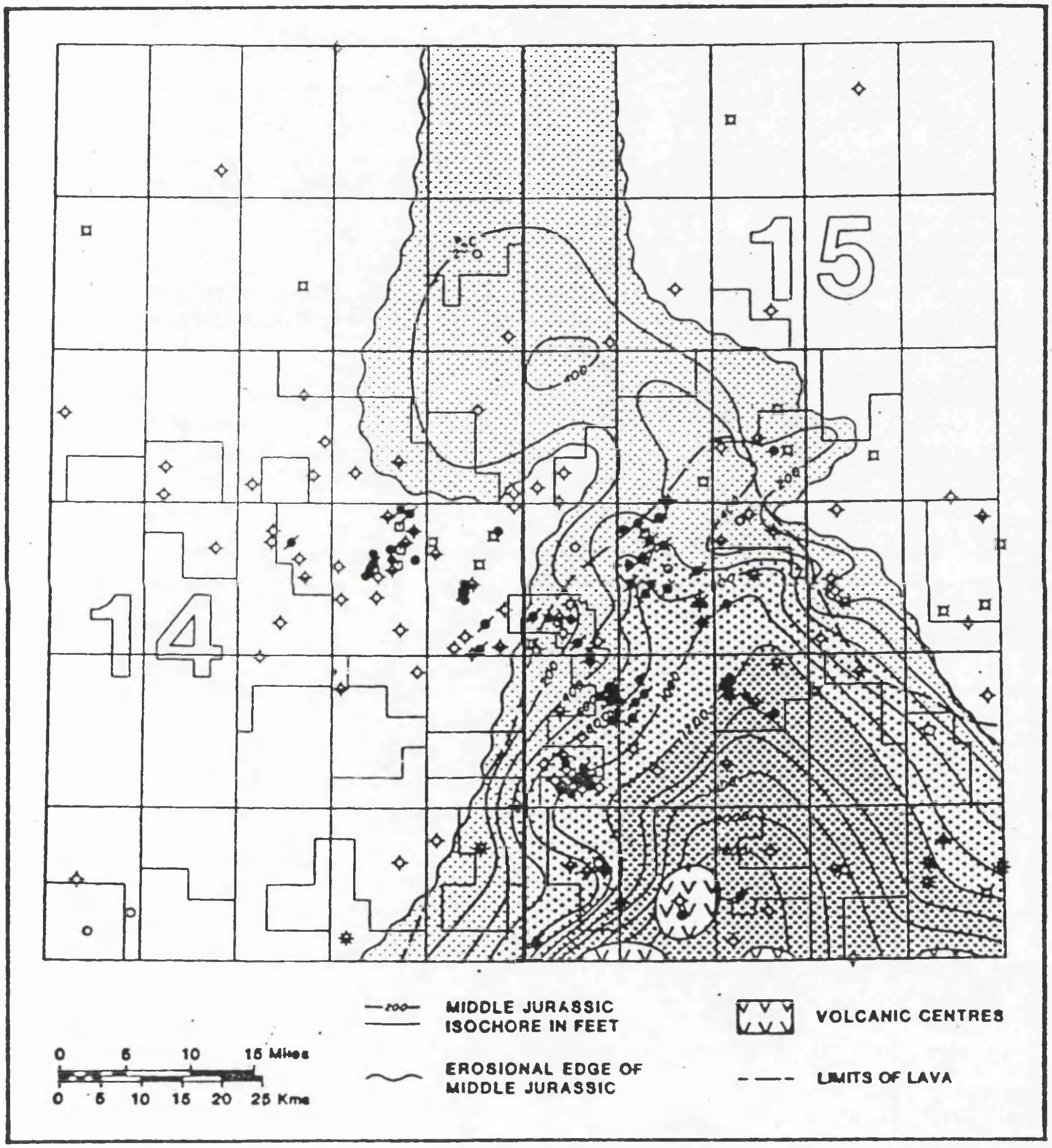


Fig. 3.15. Quadrants 14 and 15: Middle Jurassic Fladen Group distribution and thickness. From Boldy & Brealey (in press).

Tectonic controls on Sgiath and Piper Formation deposition.

In the introductory overview of regional models, the change in isochore pattern from the north-south Viking Trend of the Middle Jurassic and Sgiath/Piper Formations to the northwest-southeast "Witch Ground" Trend of the Kimmeridge Clay Formation was discussed. This transference of tectonic control is clearly demonstrated at a local level within Block 15/21.

Viking Trend fault control on the Sgiath/Piper isochore.

The isochore map for the combined Sgiath and Piper Formations has been composed using both well and seismic data (Boldy & Brealey, in press). North-northeasterly Viking trending depositional axes are prominently displayed (Fig. 3.16); the most pronounced being the Theta Graben (Fig. 1.7) where a much

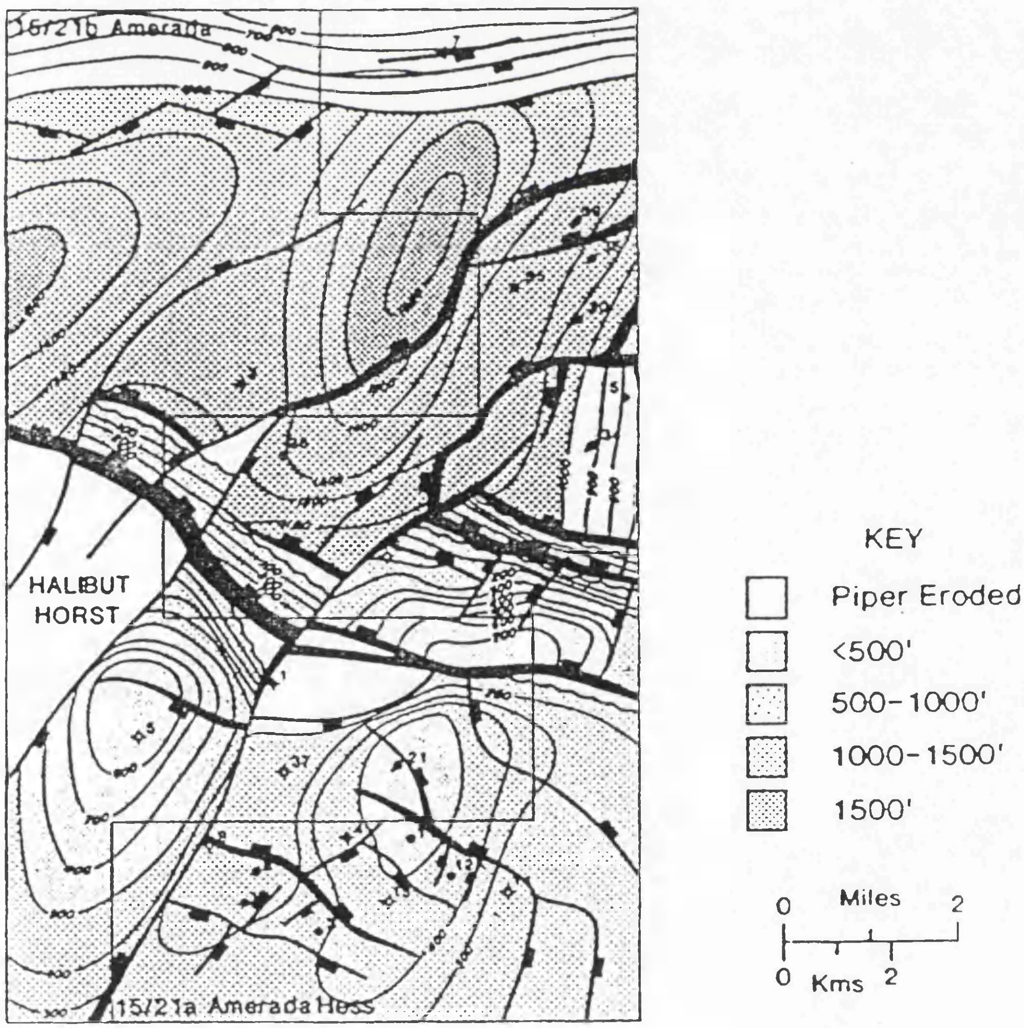


Fig. 3.16 Block 15/21: isochore map of the Sgiath and Piper Formations. From Boldy & Brealey (in press).

thicker Sgiath/Piper sequence was penetrated (15/21-5 well; 240 m+) than in wells on the Ivanhoe/Rob Roy Platform. The maximum thickness encountered was in the 15/21-2 well where the combined Sgiath/Piper interval totals 390 m; thicker sequences are postulated within the north-easterly extension of the Theta Graben where up to 500 m may be present. A parallel depositional axis is recognized through the eastern part of the Ivanhoe Field and the western part of the Rob Roy Field. Here, over 150 m of Sgiath/Piper has been proven by drilling; this thins eastwards toward Rob Roy and westward toward Ivanhoe to less than 90 m thick (Boldy & Brealey, in press).

Witch Ground Trend fault control on the Sgiath/Piper isochore.

It is clear that a strong control is exerted on the isochore pattern by the west-northwest - east-southeast Witch Ground Trend faults. Their influence on the Sgiath/Piper isochore is considered to be a function of later crestal erosion on west-northwest trending rotating fault blocks. However, these faults were not active during the deposition of the Sgiath and Piper Formations, the erosion occurring during deposition of the Kimmeridge Clay Formation.

The structural cross-section across the Theta Graben (Fig. 3.17) is orientated west-northwest - east-southeast, parallel to the major Witch Ground trending faults. It illustrates the rapid thickening of the Sgiath/Piper interval across the major down to the west fault (the Viking Trend "E" fault) that forms the eastern boundary of the graben. Across this fault there is also marked thickening of the deeper part of the section, indicating earlier, pre-Upper Jurassic movement. This is emphasised by the thickening of the Middle Jurassic volcanics. The Viking Trend faults were therefore active in Mid-Jurassic times, and controlled Sgiath/Piper deposition.

Tectonic controls on Kimmeridge Clay Formation deposition.

The isochore map of the Kimmeridge Clay Formation in Block 15/21 (Fig. 3.18) exhibits singular contrast to that for the Sgiath/Piper interval. The major depocentre is orientated in an east-west direction within the axial part of the North Halibut Graben (Fig. 1.7). This change in the thickness distribution of the sediments is related to the onset of evidential movement on the Witch Ground Trend faults, connected to the opening of the west-northwest Witch Ground Graben.

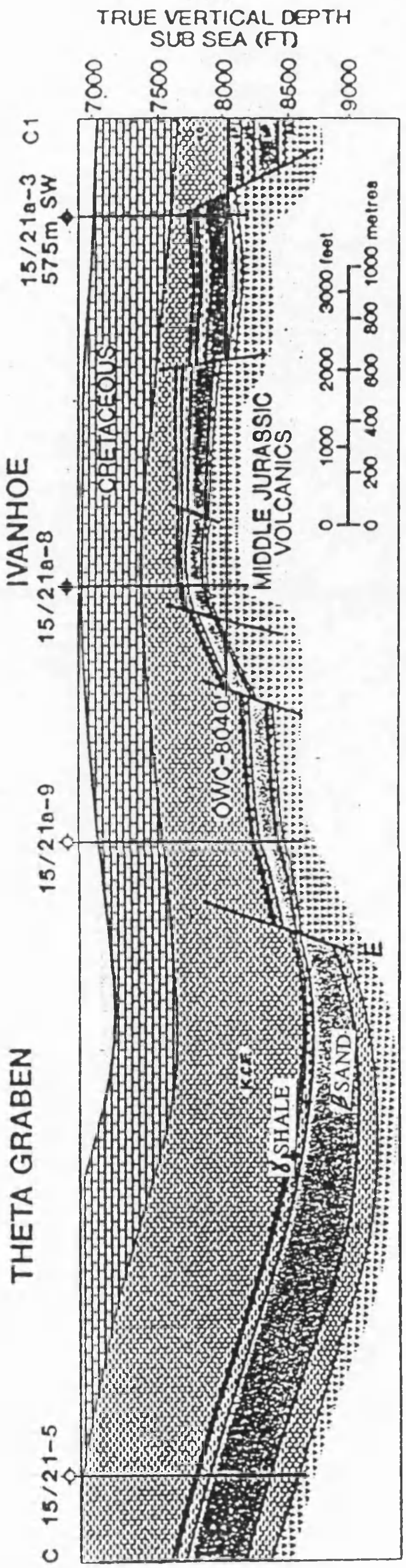


Fig. 3.17. Structural cross section through the Theta Graben, C-C1 on Fig. 1.7. From Boldy & Brealey (in press).

The Halibut Horst and its eastward continuation, the Halibut Horst Spur (Fig. 1.7), controlled by Witch Ground Trend faults are interpreted to have been uplifted during deposition of the Kimmeridge Clay Formation. On the Halibut Horst itself, and over much of the Halibut Horst Spur, there is no Kimmeridge Clay Formation preserved. Intense erosion of these areas as they were uplifted during deposition of the Kimmeridge Clay led to the removal of the Sgiath and Piper Sands, which were redeposited as submarine fan-sands (the Claymore Member and equivalents). These sands have been found both to the north (15/21-2 well) and to the south (15/21-5 well) of the Halibut Horst (Boldy & Brealey, in press).

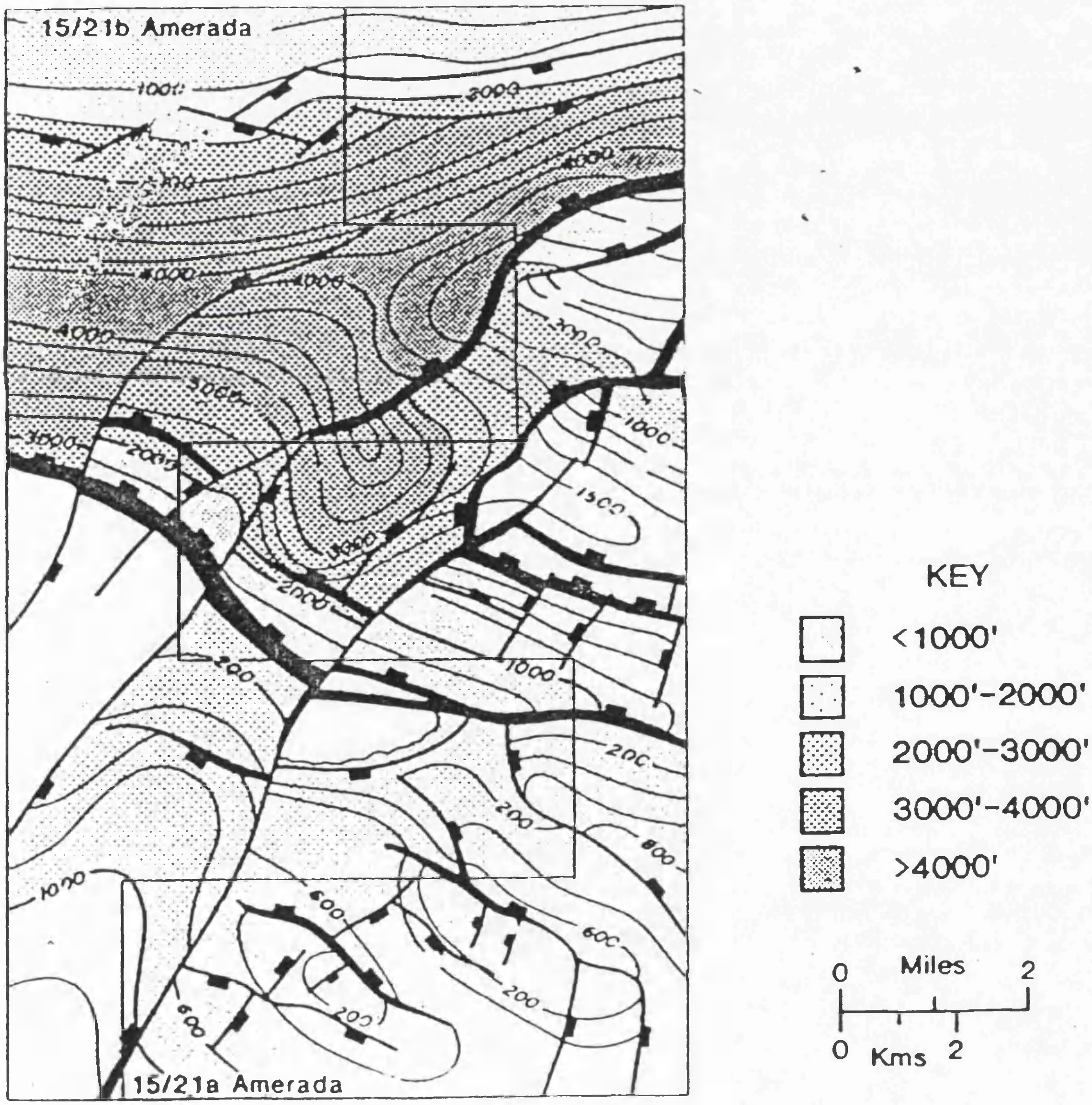


Fig. 3.18. Block 15/21: isochore map of the Kimmeridge Clay Formation. From Boldy & Brealey (in press).

Within the North Halibut Graben, tilted fault blocks are developed, commonly backtilted to the southwest. The structural traps in the Scott Field in the east of Block 15/21 are of this type; the Kimmeridge Clay Formation displays thinning over the crests of individual fault blocks. Relatively thin (up to 250 m) sequences of Kimmeridge Clay Formation occur over the Ivanhoe/Rob Roy Platform. The Ivanhoe and Rob Roy Fields are tilted fault block traps defined by Witch Ground trend normal faults, also backtilited to the southwest with the Kimmeridge Clay thinning over the crests (Boldy & Brealey, in press).

Less than 30 m is preserved over the crest of Rob Roy Field (Fig. 3.19). On the crest of the footwall adjacent to the major bounding normal faults, erosion of the uppermost Piper deposits has recently been proved during development drilling by Amerada Hess, and in places the Kimmeridge Clay may be entirely eroded. In the hanging wall block, thick sequences of Kimmeridge Clay Formation occur. This variation in thickness is not seen in the Sgiath and Piper sediments, and as the cross-section illustrates, this interval actually thickens from southwest to northeast, towards the crest of the Field. This demonstrates that the structure, and therefore movement on the Witch Ground Trend faults, postdates deposition of this sequence. A cross-section through the Ivanhoe Field also shows thinning of the Kimmeridge Clay Formation onto the crest of the structure (Fig. 3.20). The orientation of the cross-sections is orthogonal to the Witch Ground Trend faults.

9.3 REGIONAL TECTONISM AND SEDIMENTATION: DEPOSITIONAL MODEL FOR THE OUTER MORAY FIRTH.

Isochore maps of the Sgiath/Piper sequence and the Kimmeridge Clay Formation on a broader,regional scale (Figs. 3.21, 3.22) can be more clearly understood in the light of the previous observations.

The Central North Sea Graben Province was uplifted in the Late Lower Jurassic to form a broad arch (Ziegler, 1982). Fringing the northern side of this Central North Sea Dome were depositional systems responsible for the accumulation of the Pentland Formation in alluvial to marginal marine environments. Periodic volcanism occurred with some reworking into volcaniclastic sediments; together these constitute the Middle Jurassic Fladen Group.

Subsidence of the arch resulted in progressive southward onlap of the

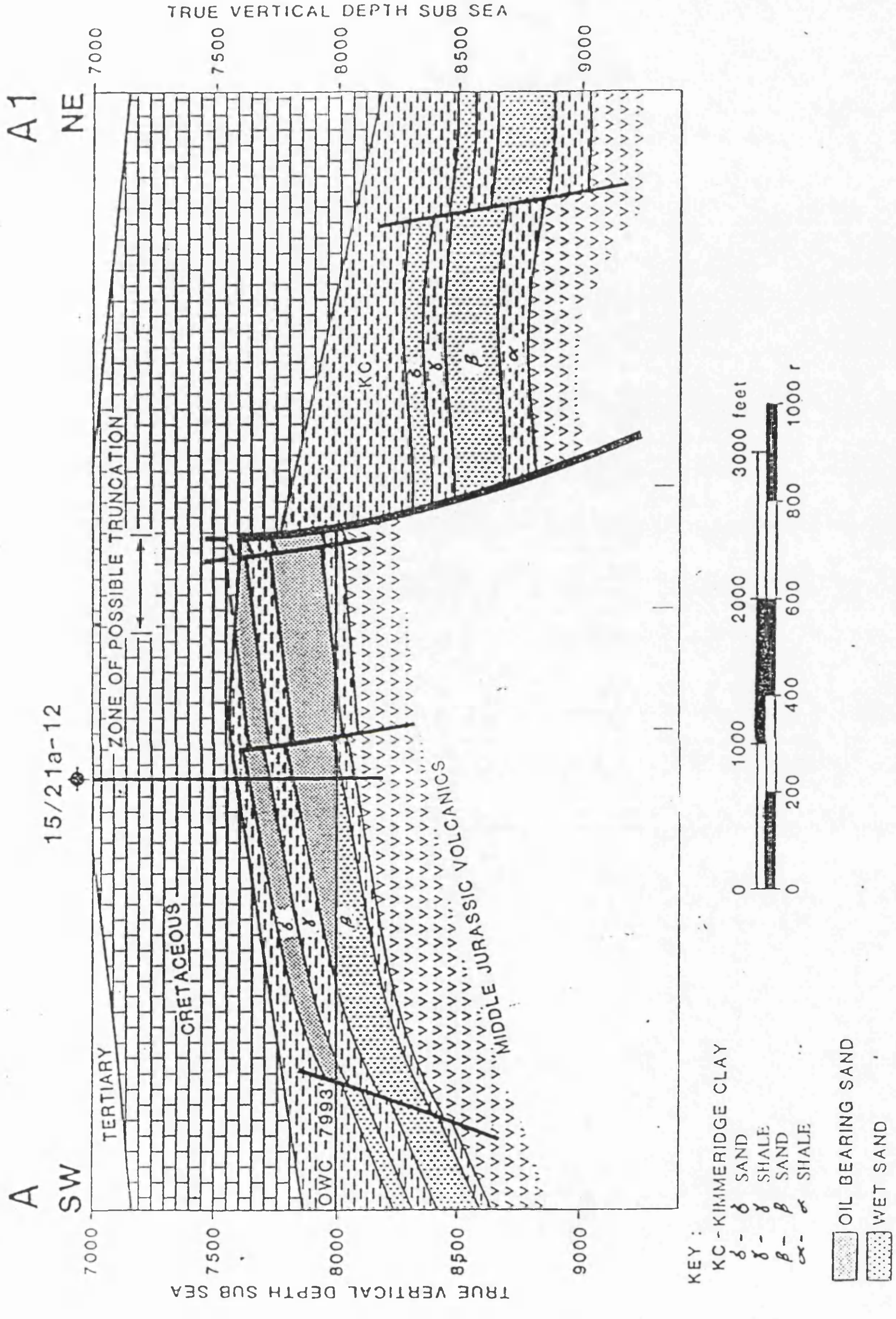


Fig. 3.19. Structural cross-section of the Rob Roy Field - A-A1 on Fig. 1.7
From Boldy & Brealey (in press).

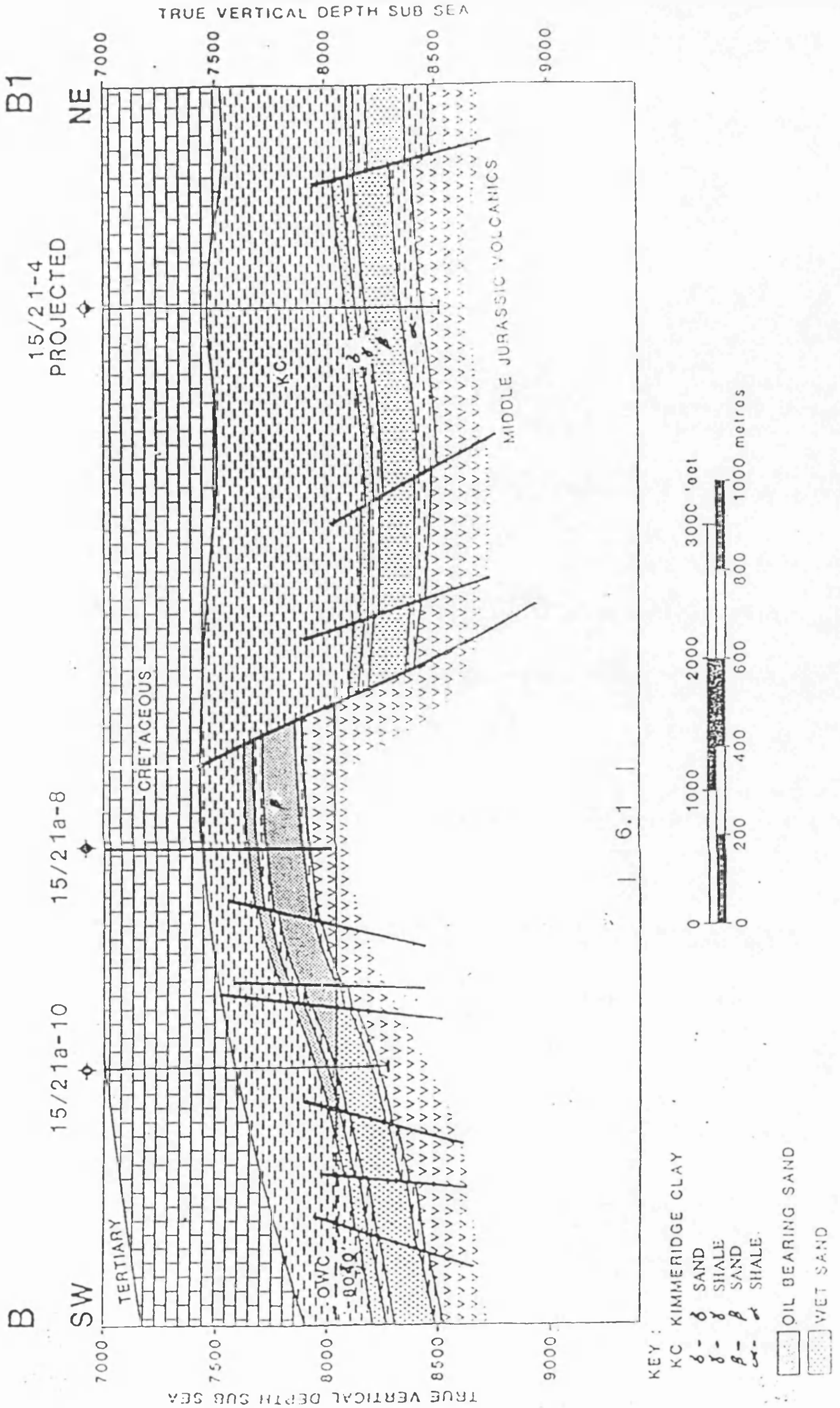


Fig. 3.20. Structural cross-section of the Ivanhoe Field - B-B1 on Fig. 1.7 From Boldy & Brealey (in press).

increasingly (Mid-Cimmerian) faulted terrain. Marine inundation was initiated in the late Mid-Oxfordian (Rawson & Riley, 1982). Erosion of the submerging arch led to the deposition of the paralics to deltaics, and with continued Late Oxfordian transgression, marine silt and muds, of the Basal Sgiath Shale Member. This transgression was strongly diachronous and was periodically reversed by brief regressive episodes as it moved across the arch in a stepwise fashion. Hence, the Bathonian Tarbert Formation of the North Viking Graben passes into the younger Callovian Beryl D and early Oxfordian Hugin Sands (Boote & Gutav, 1987). The Sgiath and Piper systems represent the latest stages of the transgression, forming part of a wave-dominated delta complex (which Boote & Gustav, 1987, extend as far south as the Fulmer area), which prograded back to the north.

The Sgiath Formation is widespread in the Witch Ground Graben, and an age equivalent coal-bearing sandstone sequence occurs in the southern Moray Firth Basin, south of the Halibut Horst (O'Driscoll *et al.*, in press). The marine shale tends to coarsen upwards into lower shoreface and finally upper shoreface delta-front sands, as sedimentation rate outpaced sea-level rise. The resultant Sgiath Sand Member is well developed in the south of the Outer Moray Firth Province (Tartan Field in the south of Block 15/17, and Block 15/21), but further north in the Piper and Claymore/Scapa areas, the Sgiath Formation is condensed, with little development of fully marine sands and shales below the Piper I Shale. Thus, the type area of the Sgiath Formation (well 14/19-4) was a relative high during Sgiath deposition.

The Piper I Shale Member is interpreted as representing renewed impetus to the late Oxfordian transgression, with relative rise in sea-level temporarily out-pacing sedimentation rate, from basal Kimmeridgian Baylei Zone to mid-Mutabilis Zone times. A second coarensing upward regressive sequence towards the top passes into the argillaceous sands and lower shoreface sequences of the Piper Sand Member, which passes laterally northward into more argillaceous units. This represents the final regressive sequence in Block 15/21, but further to the north in the Tartan area several more sands (the Upper Piper Sand and Hot Sand of O'Driscoll *et al.*, in press) are present. These represent deposition from the Fladen Ground Spur, which with rising sea-level remained emergent as the primary source area for these late Kimmeridgian sands.

Mid-Jurassic Fladen Group, Late Oxfordian Sgiath Formation, and Baylei-Mutabilis Zone Piper Formation deposition was controlled by north-south and

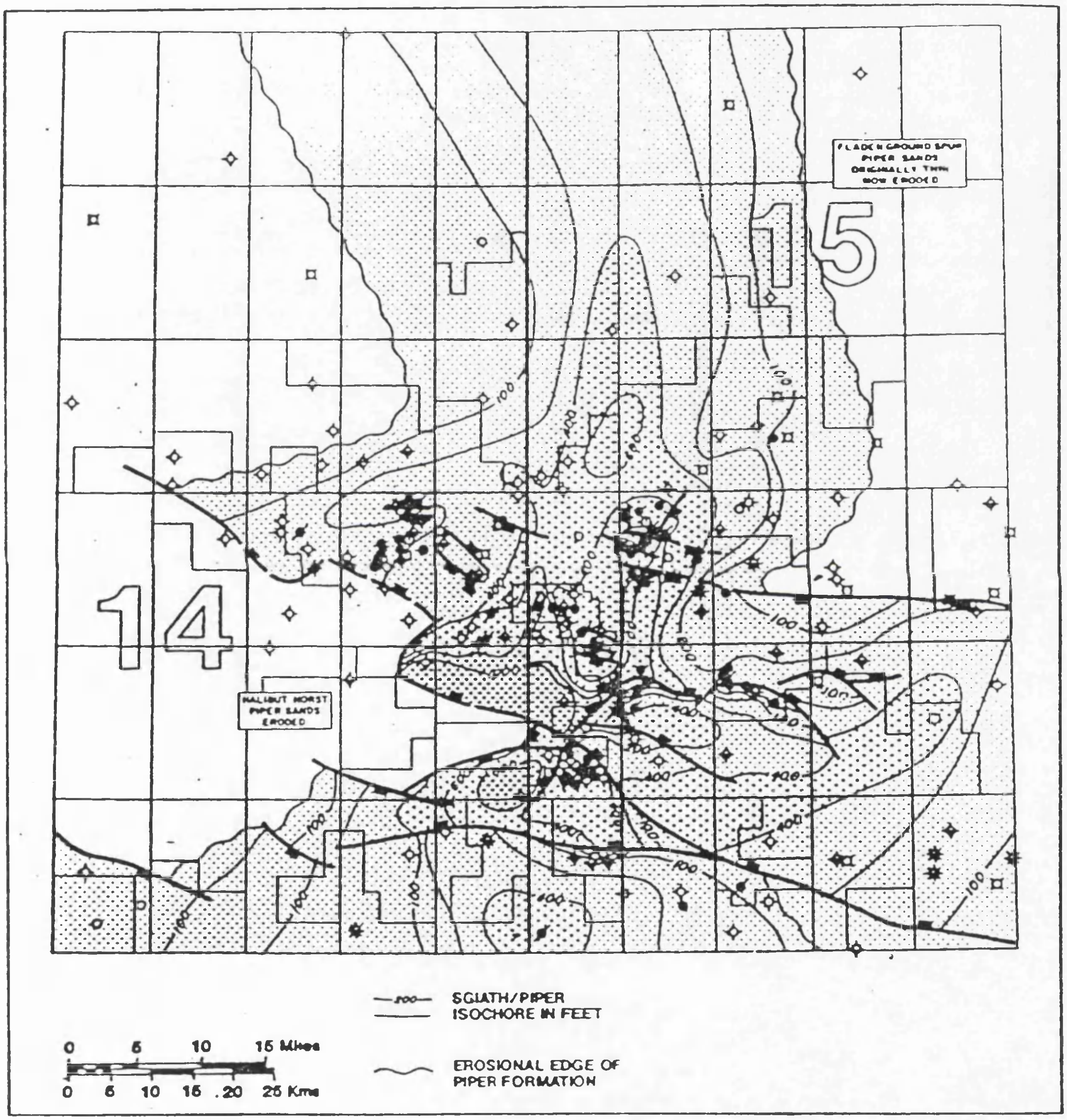


Fig. 3.21. Quadrants 14 and 15: Sgiath and Piper Formation distribution and thickness. From Boldy & Brealey (in press).

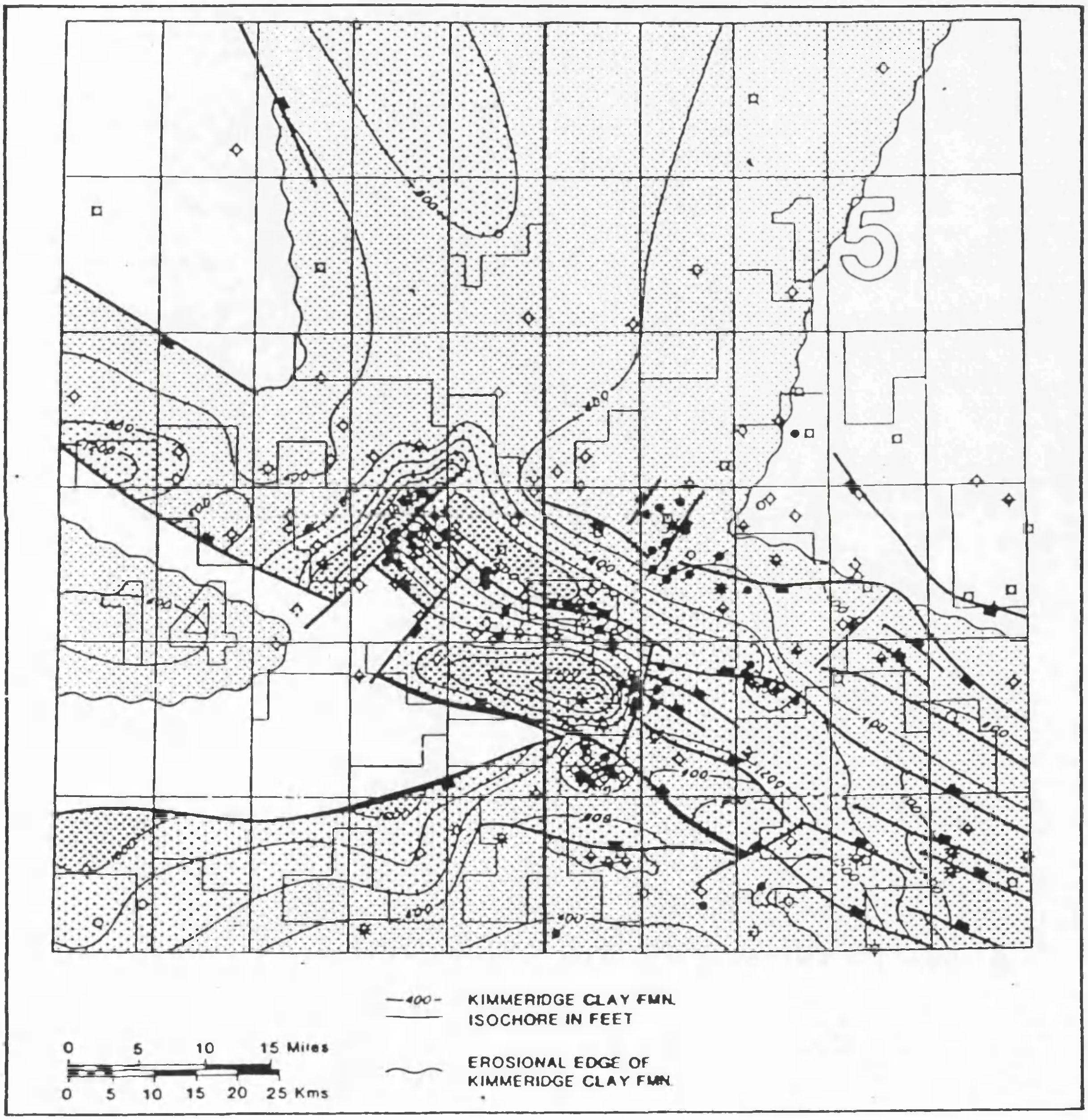


Fig. 3.22. Quadrants 14 and 15: Kimmeridge Clay Formation distribution and thickness. From Boldy & Brealey (in press).

northeast-southwest Viking Trend faults. Deposition occurred in a north-south basin, parallel to the Viking Gaben, formed by extension orthogonal to the major normal faults, in an east-west direction. Although some Witch Ground trend faults may have existed as transfer faults during this time, the major structural feature of the Witch Ground Graben had not been formed, this being realized with a major change in tectonic regime beginning in the Kimmeridgian.

Overprinting the eustatic sea-level rises during the Late Oxfordian and early Kimmeridgian are the dying effects of Mid-Cimmerian tectonism, movement on Viking Trend faults being demonstrated by thickening of the Sgiath/Piper sequence on their downthrown sides. Tectonics are more important than water depth in determining sedimentary thickness. Thus, the southwesterly thickening of the I Shale used by O'Driscoll *et al.* (in press) to support a southwest to northeast transgression is a function of local tectonics. Although no tectonic control is apparent controlling I Shale deposition in Block 15/21 (Boldy & Brealey, in press) it seems unlikely that movement on Viking trend faults was entirely restricted to times of sand deposition during regressive phases. The lack of thickness differentials on either side of Viking Trend faults is possibly a function of compaction, the greater thickness of sand on the downthrown side of the faults compacting the I Shale to a greater degree here.

It seems likely that Kimmeridge Clay transgression accompanied the onset of Late Cimmerian phase tectonism, suggesting a Eudoxus Zone age for the beginning of this tectonic event, rifting occuring in a northeast-southwest extensional regime.

During the remainder of the Jurassic, progressive collapse is illustrated by development of various, tectonically confined turbiditic systems such as the Claymore, Galley and Brae Sand Members The wave-dominated delta complex was abandoned and the strandline systems migrated south. The source of these systems was the emergent rift shoulders. The still unlithified cover of rotating fault blocks, formed by Witch Ground Trend faulting, was eroded and redeposited around the emergent structures, such as the Claymore and South Halibut systems around the Halibut Horst. These extensive sand-rich turbidites are characterised by unorganized, thin to thick-bedded or structureless sandstones with a similar composition and grain size to older Jurassic sands nearby. Similarly, the Alt-na-Cuille Sandstones of northeast Scotland, and the Hareelv Formation of East Greenland include clasts and slumped masses of older shallow marine Jurassic sands within structureless turbidites, indicating incomplete disaggregation of earlier sediments (Boote & Gustav, 1987).

The grabens receiving these turbidite systems developed at different times. The Claymore Sandstone Member of the Kimmeridge Clay Formation is late Kimmeridgian to Mid-Volgian in age, major sediment input co-inciding with late Early Volgian regression, and declining with Mid-Volgian regression. Other intra-Kimmeridge Clay sands, for example the Galley and Brae systems, are locally as young as latest Mid-Volgian (Harker *et al.*, 1984). With increasing relief, scarp-face erosional retreat shed detritus in strike-parallel fan aprons during the latest Jurassic and Early Cretaceous (eg. the Valhall Formation and Scapa Sands) into an increasingly restricted tectonic fabric of collapsing grabens associated with extensional collapse of the Witch Ground Graben and the main phase of Late Cimmerian tectonism.

In conclusion, the Ivanhoe, Rob Roy, Scott and Piper Fields are all tilted fault block traps defined by Witch Ground Trend faults, and were formed during Kimmeridgian (Eudoxus Zone onwards) to early Cretaceous times. The Witch Ground Graben is a symmetrical feature with fault blocks backtilted to the northeast in the north (Piper Field - Fig. 3.23) and to the southwest in the south (Ivanhoe, Rob Roy, Scott Fields). These Witch Ground Trend faults exert an influence on the isochore pattern of the Sgiath and Piper Formations, through erosion of the tilted fault block crests, and controlled the distribution of the Claymore Member sands and their equivalents in the Late Kimmeridgian and Volgian, which Boote & Gustav (1987) showed to have accumu ted as toe of slope submarine fans.

9.4 A COMPARISON WITH EVENTS IN EAST GREENLAND.

Other than those in the northeast of Scotland and in Skye, the nearest successions on land which can serve for comparison with the northern North Sea are those in East Greenland, today 1,500 km to the northwest (Fig. 3.24). If Greenland is restored to its Jurassic position this distance is reduced by approximately two thirds.

Correlation of the Upper Oxfordian/Kimmeridgian presents few problems due to the well documented ammonite successions (Spath, 1935, 1936; Sykes & Surlyk, 1976; Callomon & Birkelund, 1980; Birkelund & Callomon, 1985 etc.). The

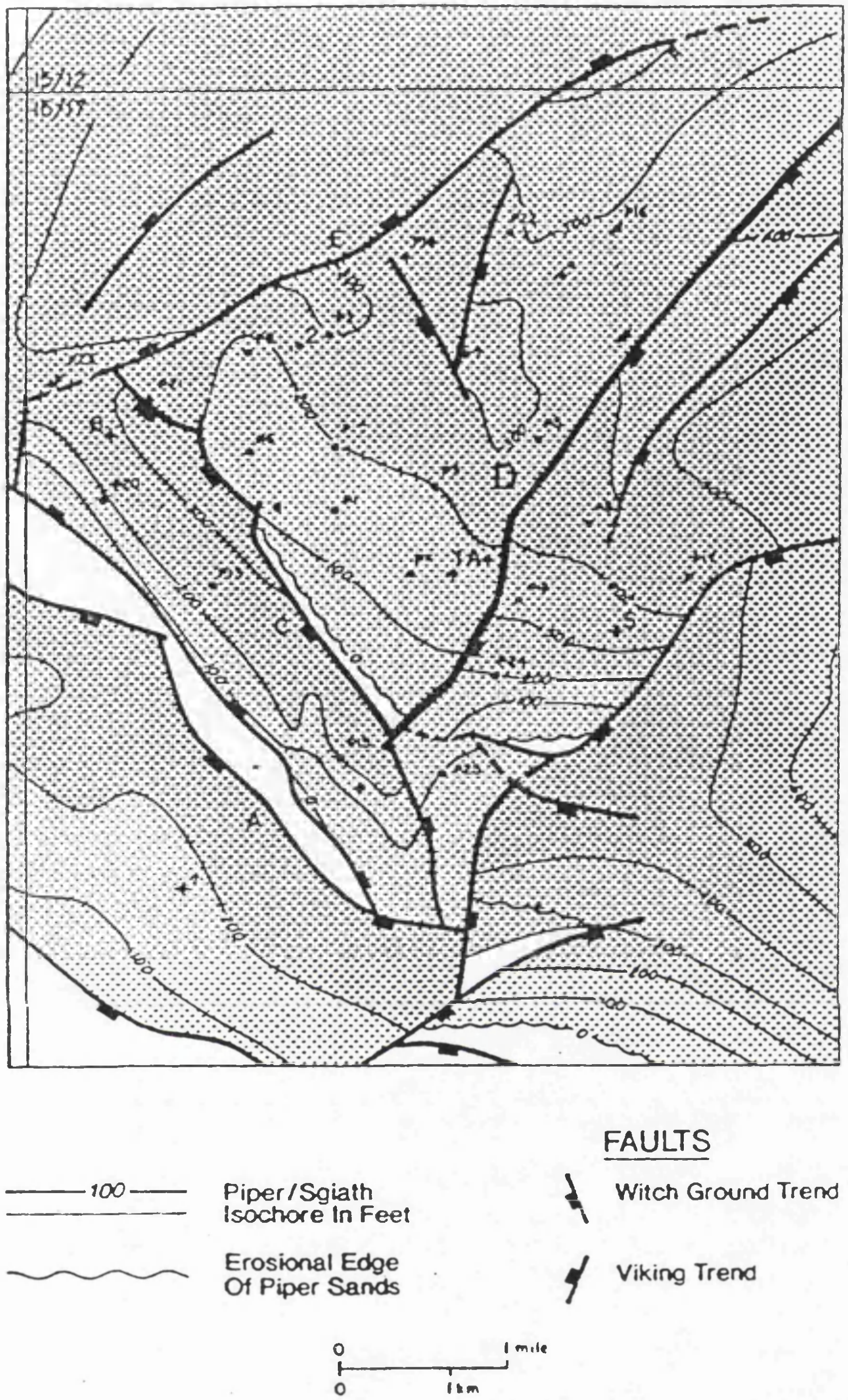


Fig. 3.23. Block 15/17: isochore map of the Sgiath and Piper Formations highlighting fault trends (after Maher, 1980). From Boldy & Brealey (in press).

ammonites recovered from North Sea boreholes closely resemble forms found in the Hareelv Formation in Jameson Land, the Kap Leslie Formation in Milne Land, and the Ampthill and Kimmeridge Clays or their equivalents in Scotland and eastern England. The facies of "black shales" are very similar except in that they become highly micaceous, silty and almost non-argillaceous in Greenland. The relationship between facies distributions and tilted fault block geometry has been

UPPER JURASSIC OUTCROP

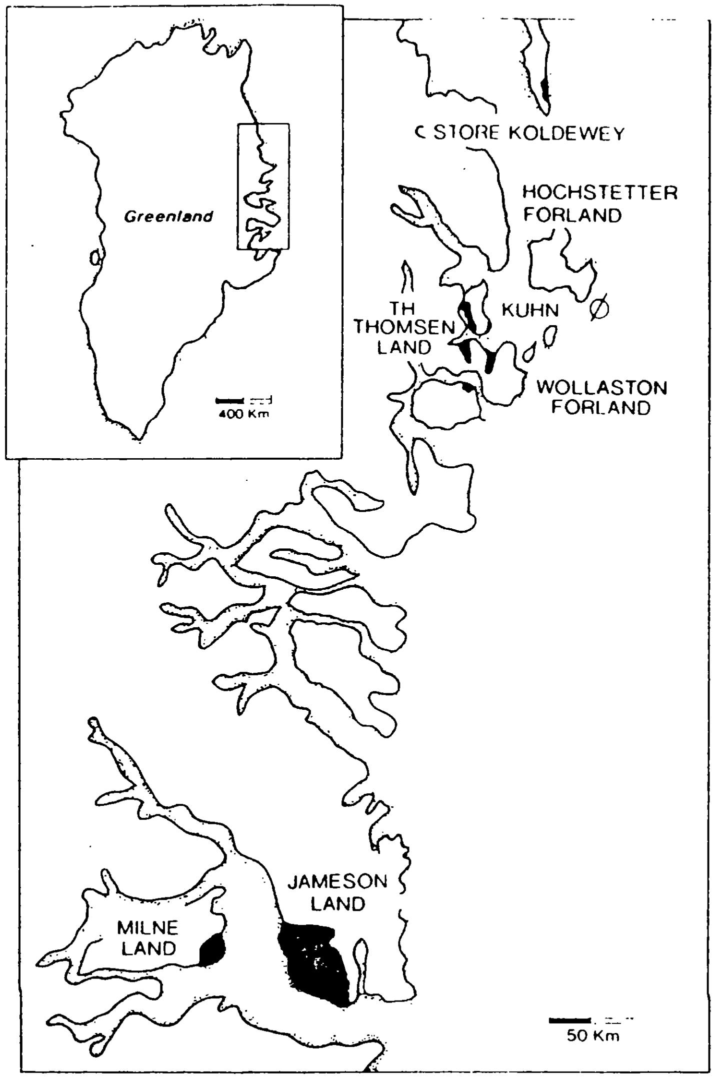


Fig. 3.24. Upper Jurassic outcrop in East Greenland, with the localities mentioned in the text

investigated in the light of the excellent biostratigraphic control (Sykes & Surlyk, 1976; Surkyk & Clemmenson, 1983; Surlyk, 1977, 1978, 1987 etc.).

Jurassic sedimentation in East Greenland took place in two tectonically controlled depocentres; the Jameson Land embayment to the south, and the Wollaston Forland embayment to the north (Surlyk, 1990). The Middle Jurassic in the Jameson Land embayment was characterized by uplift of its borders and the influx of large amounts of sands and muds of the Pelion Member of the Vardekløft Formation, overlying Toarcian to Aalenian dark, marine shales. The Wollaston Forland embayment was first transgressed at this time, the Bathonian to Lower Callovian Pelion sandstones resting directly on the peneplained basement (Surlyk, 1977). The Pelion Member is strongly diachronous, younging northward towards the source area. The start of sea level rise can be dated to basal Bathonian, where the shallow marine sandstones of the Pelion Member in southern Jameson Land give way to the overlying offshore shales of the Fossilbjerget Member.

A final progradational phase was initiated in Jameson Land in the Upper Callovian, with deposition of the sand-dominated Olympen Formation until the Middle Oxfordian. Further south this interval is represented by a condensed transitional sequence between the Fossilbjerg Member and overlying deep-water shales and turbiditic sands of the Hareelv Formation.

In the Wollaston Foreland embayment the Pelion Member is overlain by the Early to Late Oxfordian Jakobsstigen Member, shoreface deposits and more proximal equivalents correlative with the Olympen Formation.

In Jameson Land the change to deep-shelf mudstones and turbiditic gully sandstones of the Hareelv Formation took place in the Oxfordian, the whole basin being submerged by Late Oxfordian times, while silty mudstones and offshore bar sands were deposited in Milne Land (the Kap Leslie Formation) (Callomon & Birkelund, 1980). This corresponds to the dark mudstones of the Upper Oxfordian to Lower Volgian Bernbjerg Formation in the Wollaston Foreland basin. An upwards change to more kerogen- and organic-rich finer-grained shales indicates that sea-level continued to rise reaching a highstand in the Kimmeridgian Eudoxus Zone (Surlyk, 1990) (Fig. 3.25).

Black shale deposition was terminated in the Early Volgian in Jameson Land by the incoming of Raukelv Formation coarse clastics, connected to an increase in tectonic activity. In Milne Land the change is gradual, whilst in Jameson Land the change from the Hareelv Formation to the sandstones of the Raukelv Formation occurs over a few metres. In Wollaston Foreland, a phase of rotational block-faulting was initiated in Middle Volgian times.

Sea Level Curves: Eustasy and tectonic controls.

The abrupt vertical changes to deeper and more offshore facies described above may have several different causes, or combinations of causes. The most important might be imagined to be eustatic and regional sea-level changes, but to what extent are these overprinted by subsidence along the main faults over long periods of time, or by periods of block faulting and tilting? Sedimentological criteria can facilitate interpretation of palaeo-water depth; Surlyk (1990) has combined evidence from several sections spanning the same time interval in an effort to interpret regional sea-level changes in East Greenland.

Two curves, for the Jameson Land and Wollaston Foreland embayments are

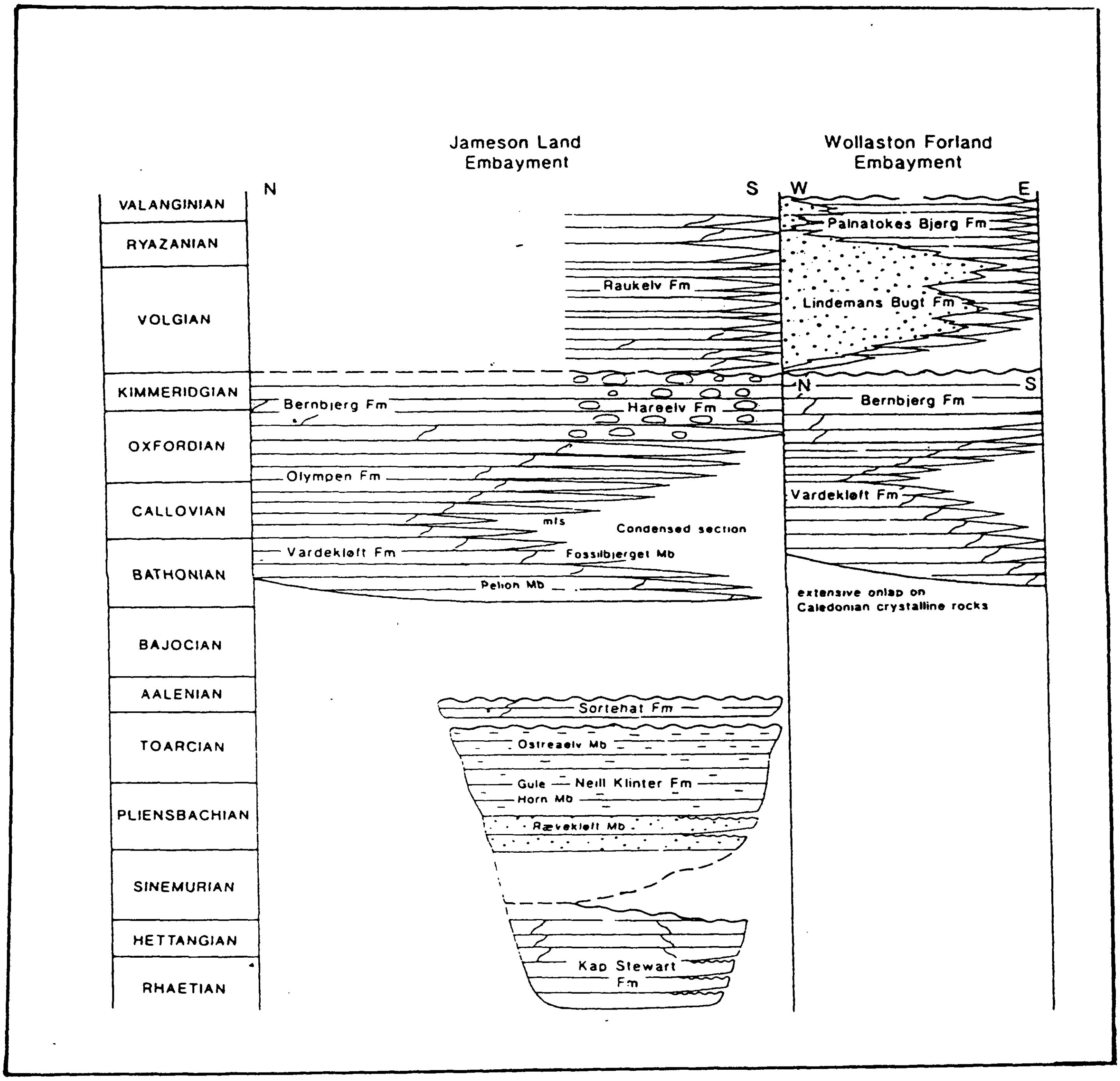


Fig. 3.25. East Greenland sequence correlations (after Surlyk, 1990).

considered to reflect the same general trends in sea-level (Fig. 3.26). The curves show an overall positive correlation with the eustatic curve of Hallam (1988), describing a rise in sea-level throughout the Jurassic which is probably of a euastic nature. Haq *et al.*'s (1987) curve deviates in the Late Jurassic by numerous short-term deflections. The good match between the curves increases the potentiality of separating eustatic signals from those caused by regional tectonics. The short-term fluctuations of the curves are probably of tectonic nature. The curves of Haq *et al.* (1987) and Hallam (1988) have a strong North Sea bias, and the onset of short-term deflections in the Oxfordian probably reflects earlier initiation of block faulting in the North Sea than in East Greenland.

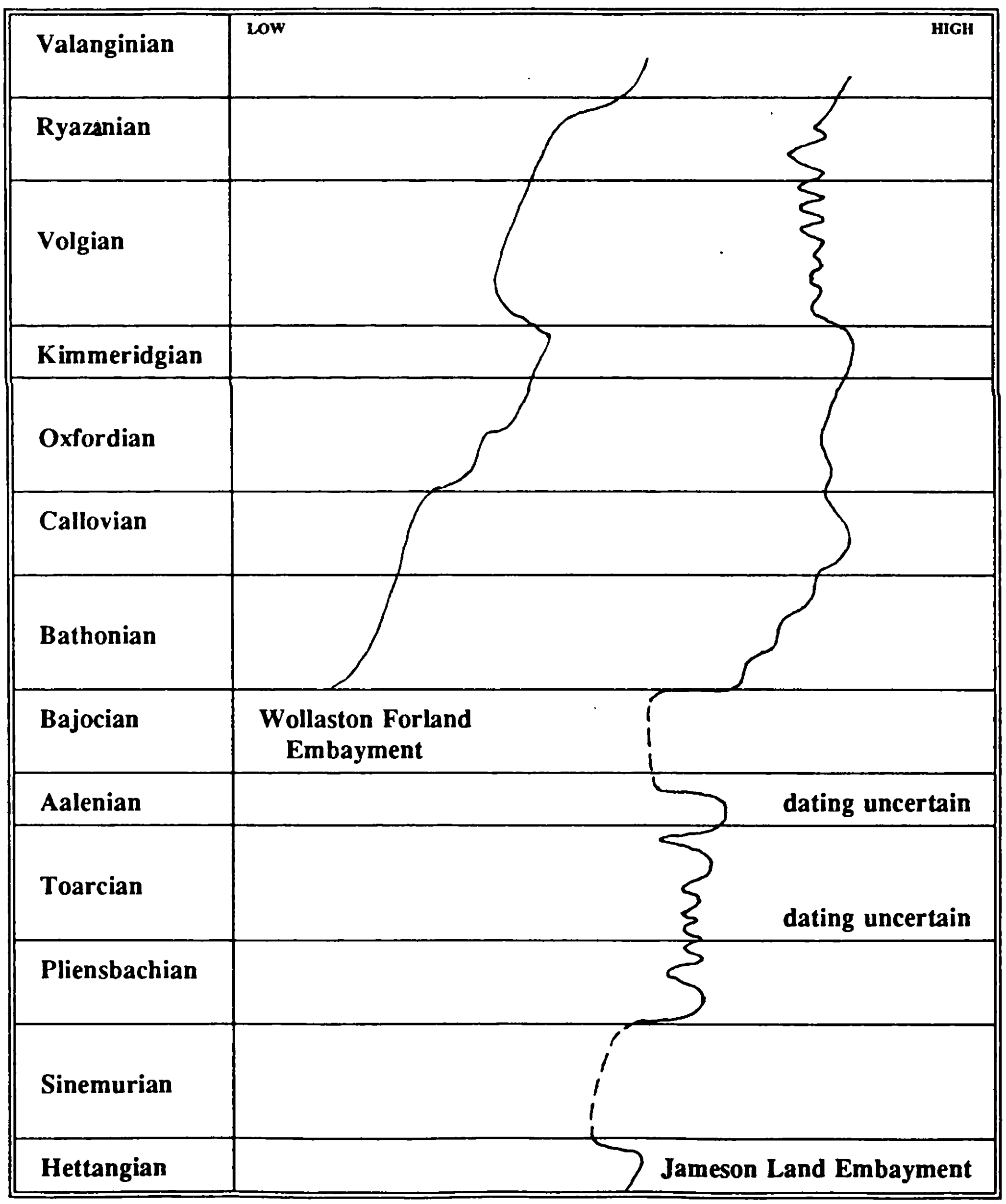


Fig. 3.26. East Greenland sea-level curves (after Surlyk, 1990).

Against the background of a eustatic rise in sea-level during the Late Jurassic, the area can be examined for the effects of tectonics on the succession. The varied nature of these successions is due to the structural style, East Greenland being part of the same rift zone as the northern North Sea, where the tilted fault block controls sedimentary phasing. Continuous sequences in the down-tilted parts of the blocks reveal phases of subsidence.

In Milne Land in the south of the area, three phases of sedimentation and subsidence can be recognized. The Caledonian basement was transgressed in Mid-Oxfordian times, and the Charcot Bugt Formation fluvially influenced marine sandstones deposited. With further subsidence shelf siltstones of the Bernbjerg Formation were deposited during the Late Oxfordian, with development of laminated basinal mudstones in the Kimmeridgian (Sykes & Surlyk, 1976).

The Vardekløft and Bernbjerg Formations of northern East Greenland were deposited during a phase of regional transgressions, probably controlled by faulting in the basement, which the spatial distribution of facies would suggest was mainly along north-south trending lines (Surlyk, 1977). The diachronous nature and stepwise reduction in thickness of the Pelion Member between progressively more northern blocks suggests earlier transgression and initiation of block faulting in the south than in the north, as witnessed by earlier faulting episodes in the North Sea than in Greenland. This pattern is repeated through the sequence. In the Wollaston Foreland block, the Upper Oxfordian mudstone facies continues into the lower Kimmeridgian, whereas in the next block north of here (Kuhn Ø), lower Kimmeridgian Bernbjerg mudstones overlie the Pelion sandstones, testifying to a major down-faulting of this block in early Kimmeridgian times.

A general model for Jurassic sedimentation and tectonics in East Greenland involves the development of north-south depositional troughs formed by faulting in the basement, with subsidence taking place by gradual movements along the faults. The general north-south pattern was cut by a number of northwest-southeast trending faults (downthrowing to the south) which seem to have been activated in a series of violent movements reflected by reductions in thickness or disappearance of formations when passing from south to north (Surlyk, 1977).

The most dramatic facies change is from the sand dominated Vardekløft Formation to the Bernbjerg mudstones in the Late Oxfordian and Kimmeridgian.

The incoming of dark mudstones at this time is characteristic throughout the northern North Sea-North Atlantic region, as a result of Jurassic eustatic sea-level rise. However, detailed stratigraphic analysis has shown that the vertical facies change is due to some extent to control by basement faulting. This interpretation is supported by rapid lateral change to coarser sediments in the vicinity of depocentre-bordering faults. The sea-level curves show fault-controlled submergence and transgression with an overprint of eustatic sea-level rise.

9.5 CONCLUSIONS.

The recovery of ammonites from cores has allowed precise ages to be assigned to sedimentary units in the Outer Moray Firth, which previously have been dated incorrectly using dinoflagellate cysts. This was due primarily to the fact that offshore dinoflagellate cyst stratigraphy was taken as being identical to that in areas onshore, such as the Dorset coast, where dinozonal boundaries were tied in with ammonite zones during the establishment of the zonal schemes. If the ammonite zones are taken as the standard, the dinoflagellate cyst stratigraphy clearly varies, and the dinoflagellate cysts show different ranges in the offshore area. *Scriniodinium crystallinum* and *Endoscrinium galeritum* range up to the mid-Mutabilis Zone offshore, whereas they top in the Baylei and Cymodoce Zones respectively onshore. *Aldorfia dictyota pyra* and *Stephanelytron scarburghense* have their range-tops in the mid-Mutabilis Zone offshore, rather than being present up to the top of the zone, and *Perissiaesphaeridium pannosum* appears in the mid-Mutabilis Zone rather than at the base of the zone. However, although ammonites are the superior tools for biostratigraphic use, it is not usually practical to use them commercially due to the cost of coring a well, and the logistics of storage and transport. In such situations dinoflagellate cysts provide a practicable alternative, with a high degree of accuracy in regional dating. This study has shown that their use should be qualified to account for any biogeographic influence on their stratigraphic distribution.

The improved biostratigraphic control, obtained by drawing together two disparate biostratigraphic schemes, has proved sound and practical as a tool for a more refined elucidation of the sedimentary and tectonic history of the area, and for determining the influence on this of various structures. Late Mid-Oxfordian inundation of the subsiding Central North Sea Dome led to deposition of increasingly marine sediments and delta-front sands (the Sgiath Sand) as sedimentation rate outpaced relative rise in sea-level in the latest Oxfordian. With renewed impetus to the transgression from the very beginning of the Kimmeridgian, open marine shales were deposited from Baylei to mid-Mutabilis Zone times, before the second regressive sequence of sands (the Piper Sand) accumulated to the north of the Central North Sea arch, passing into more argillaceous units further from the source. The province was eventually drowned by the base-Eudoxus transgression, which was accompanied by the onset of Late Cimmerian tectonics. Accurate dating has allowed the lateral variation in sedimentary thicknesses across the Witch Ground Graben to be understood more clearly through improved correlation, and provided a new standard to follow.

Comparison on a broader scale within the Boreal realm has provided a more accurate assessment of which events are related to local tectonism and which reflect global/regional sea level change. The effects of the transgressive events responsible for the deposition of the Sgiath and Piper Formations can be seen in Northeast Greenland, the change from sand dominated Vardekløft Formation to the Bernbjerg mudstones in the Late Oxfordian and Kimmeridgian testifying to a period of global sea level rise. Short term deflections in sea-level curves biased towards the North Sea sequences can be related to periods of block faulting; the localised lateral extent of deposits such as the Claymore Sandstones to the north of the Halibut Horst and their location within the deep water Kimmeridge Clay Formation enables us to determine their origin as tectonic, and the initiation of localised tectonism can now be dated with increased certainty.

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PLATES.

PLATE 1

Magnification: all figures x320 unless otherwise stated.

Adnatosphaeridium caulleryi (Deflandre)

Fig. 1. 15/21a-25 8403'

Fig. 2. Apex lacking. 15/21a-25 8403'

Fig. 3. 15/21a-25 8403'

Aldorfia dictyota pyrum (Gitmez)

Fig. 4. 15/21a-25 8403'

Chytroeisphaeridia chytroeides (Sarjeant)

Fig. 5. 15/21a-25 8403'

Cleistosphaeridium ehrenbergii (Deflandre)

Fig. 6. Apex lacking. 15/21a-25 8403' x480

Cleistosphaeridium tribuliferum (Sarjeant)

Fig. 7. 15/21a-25 8403'

Fig. 8. Apex lacking. 15/21a-25 8403'

Cribroperidinium globatum (Gitmez & Sarjeant)

Fig. 9. 15/21a-25 8270'

Cribroperidinium sp. A.

Fig. 10. 15/21a-25 8270'

Cribroperidinium cf. ***granuligerum*** (Klement)

Fig. 11. 15/21a-25 8270'

Cribroperidinium longicorne (Downie)

Fig. 12. 15/21a-25 8391'

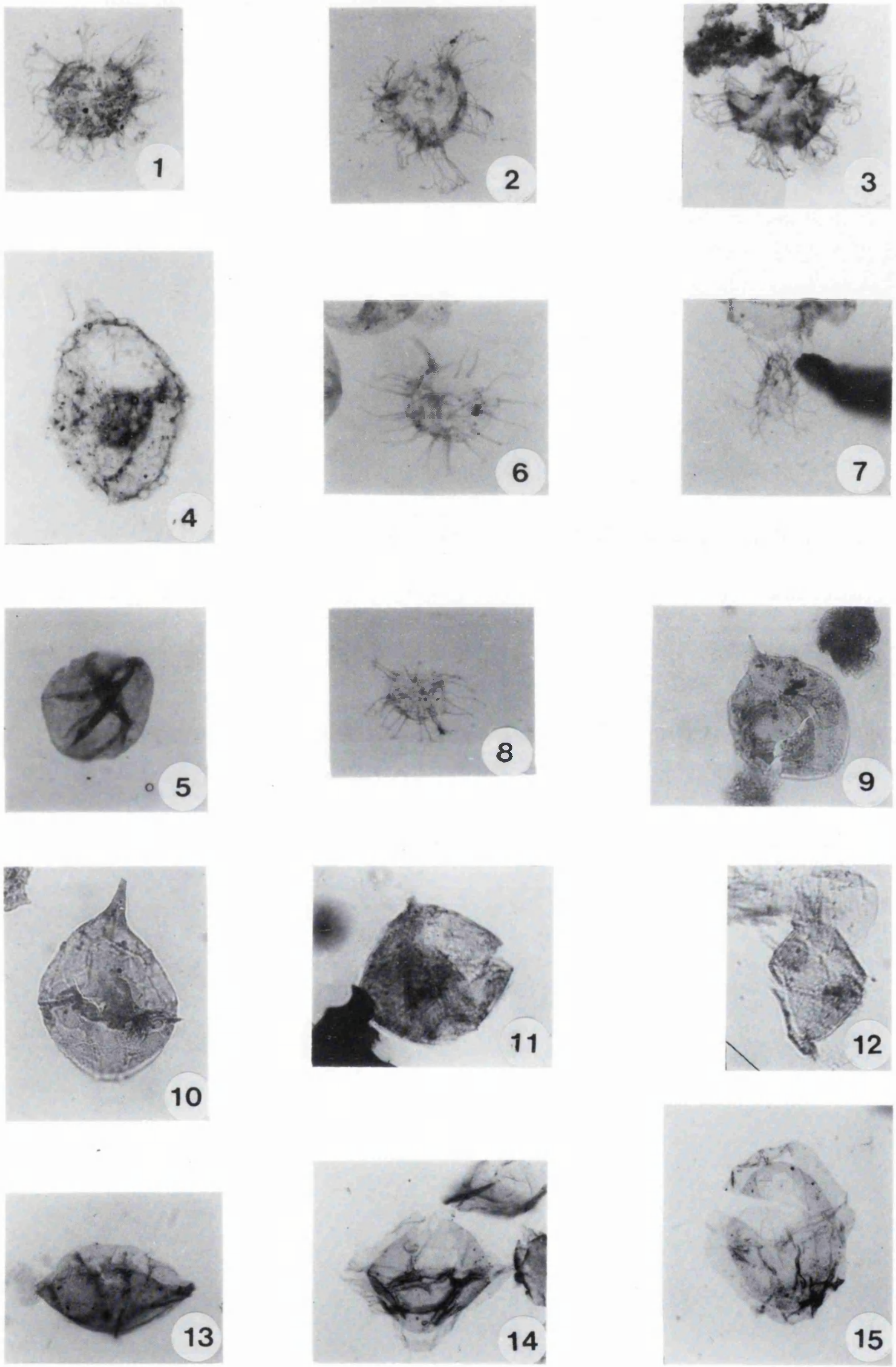

PLATE 1

Ctenidodinium chondrum Drugg

Fig. 13. Showing epicystal archaeopyle. 15/21a-25 8403'

Endoscrinium galeritum (Deflandre)

Fig. 14. 15/21a-25 8403'

Endoscrinium luridum (Deflandre)

Fig. 15. 15/21a-25 8403'

PLATE 2

Gonyaulacysta jurassica jurassica Deflandre

Figs. 1-3. 15/21a-25 8403'

Gonyaulacysta jurassica longicornuta Sarjeant

Figs. 4,5. 15/21a-25 8403'

Glossodinium dimorphum Ioannides *et al.*

Fig. 6. 15/2125 8270'

Hystrichosphaeridium petilum Gitmez

Fig. 7. 15/21a-25 8403' x480

Perissieasphaeridium pannosum Davey & Williams

Fig. 8. Apex lacking. 15/21a-25 8270'

Fig. 9. Apical view. 15/21a-25 8270'

Perissieasphaeridium ingegerdii Nøhr-Hansen

Fig. 10. Apex lacking. 15/21a-25 8270,

Fig. 11. Same specimen - x480

Prolixosphaeridium granulosum (Deflandre)

Fig. 12. Apex lacking. 15/21a-25 8403' x480

Fig. 13. 15/21a-25 8403' x480

Rhynchodiniopsis cladophora (Deflandre)

Fig. 14. 15/21a-25 8403'

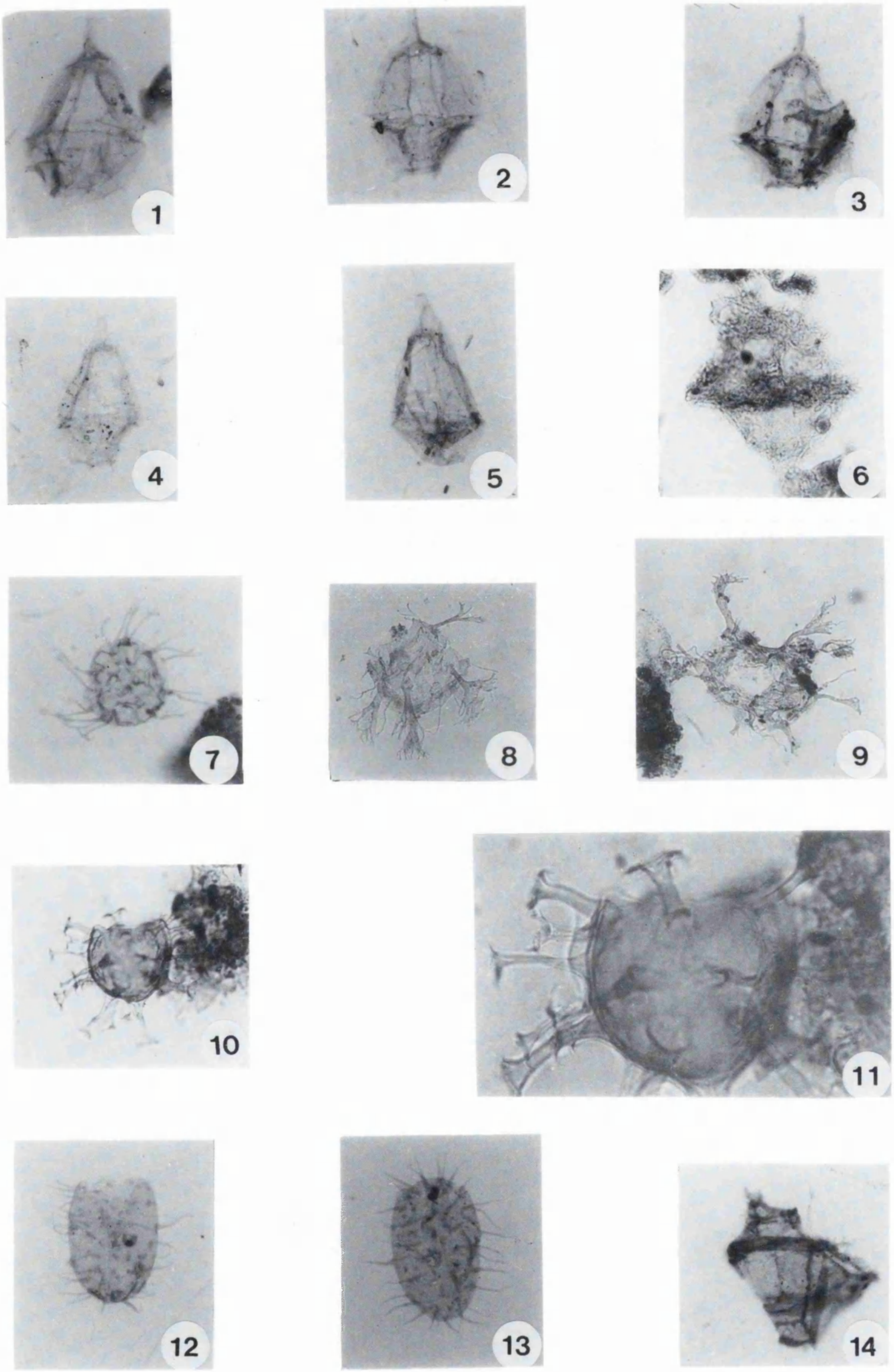

PLATE 2

PLATE 3

Rhynchodiniopsis cladophora (Deflandre)

Figs. 1-3. 15/21a-25 8403'

Scriniodinium crystallinum (Deflandre)

Fig. 4. 15/21a-25 8403'

Sirmiodinium grossi Alberti

Fig. 5. 15/21a-25 8391'

Systematophora areolata Klement

Fig. 6. 15/21a-25 8403'

Stephanelytron cf. ***scarburghense*** Sarjeant emend. Stover *et al.*

Fig. 7. 15/21a-25 8403' x480

Tubotuberella apatella (Cookson & Eisenack)

Fig. 8. 15/21a-25 8403'

Spiniferites ramosus group (Ehrenberg)

Fig. 9. Cretaceous or Tertiary contaminant. 15/21a-25 8270'

Fig. 10. Cretaceous or Tertiary contaminant. 15/21a-25 8270' x480

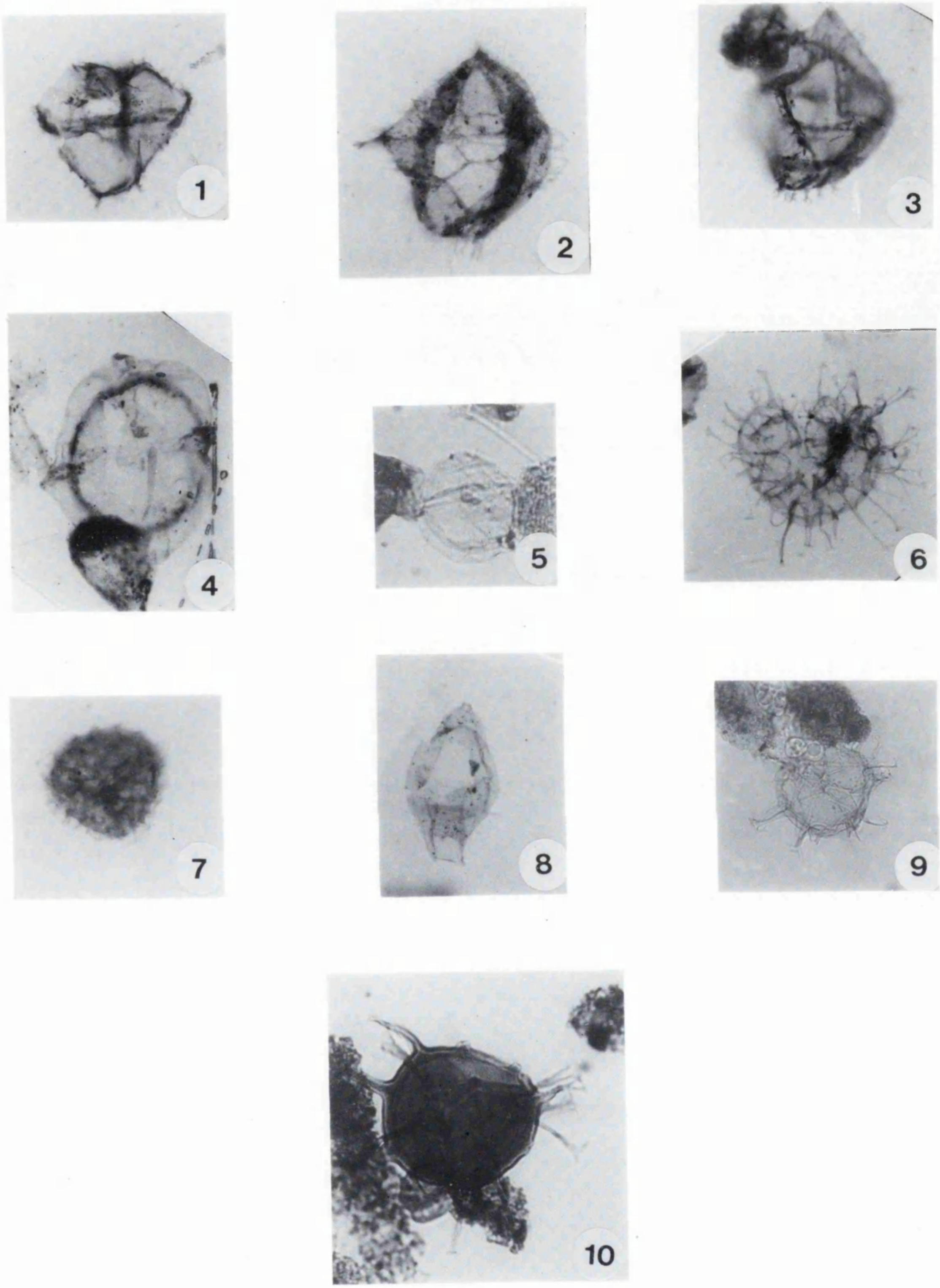

PLATE 3

PLATE 4

Amoeboceras (Amoebites) bauhini (Oppel)

Fig. 1. 15/21a-15 1131'3"

Fig. 2. South Ferriby 90.7.27./1 Bed 16

Fig. 3. South Ferriby 88.5.19/25 Bed 14

Fig. 4a, b. South Ferriby 90.7.27.2 Bed 16

Amoeboceras (Amoebites) cf. *subkitchini* Spath

Fig. 5. 15/21a-12a 7937'

Amoeboceras (Amoebites) kitchini (Salfeld)

Fig. 6. Eathie M1501. From the collection of Dr. P. F. Rawson, University College, London.

Fig. 7. Eathie B25/11

Amoeboceras (Amoebites) rasenense Spath

Fig. 8. Eathie B25/24

Fig. 9. Eathie B25/8

Amoeboceras (Amoebites) cricki (Salfeld)

Fig. 10. South Ferriby 88.5.17/24

Fig. 11. 15/21a-11 7859'9"

Amoeboceras (Amoebites) beaugrandi (Sauvage)

Fig. 12. Lothbeg Point B23/21

*

Fig. 13. Eathie B25/5' Casts (see also Pl. 7, Fig. 7)

a. *Amoeboceras (Amoebites) rasenense* Spath

b. *Rasenia (Rasenioides)* cf. *lepidula* (Oppel)

c. *Rasenia (Rasenioides) askepta* Ziegler

Figs. 1-5, 10, 11 magnification x1.5; others natural size.

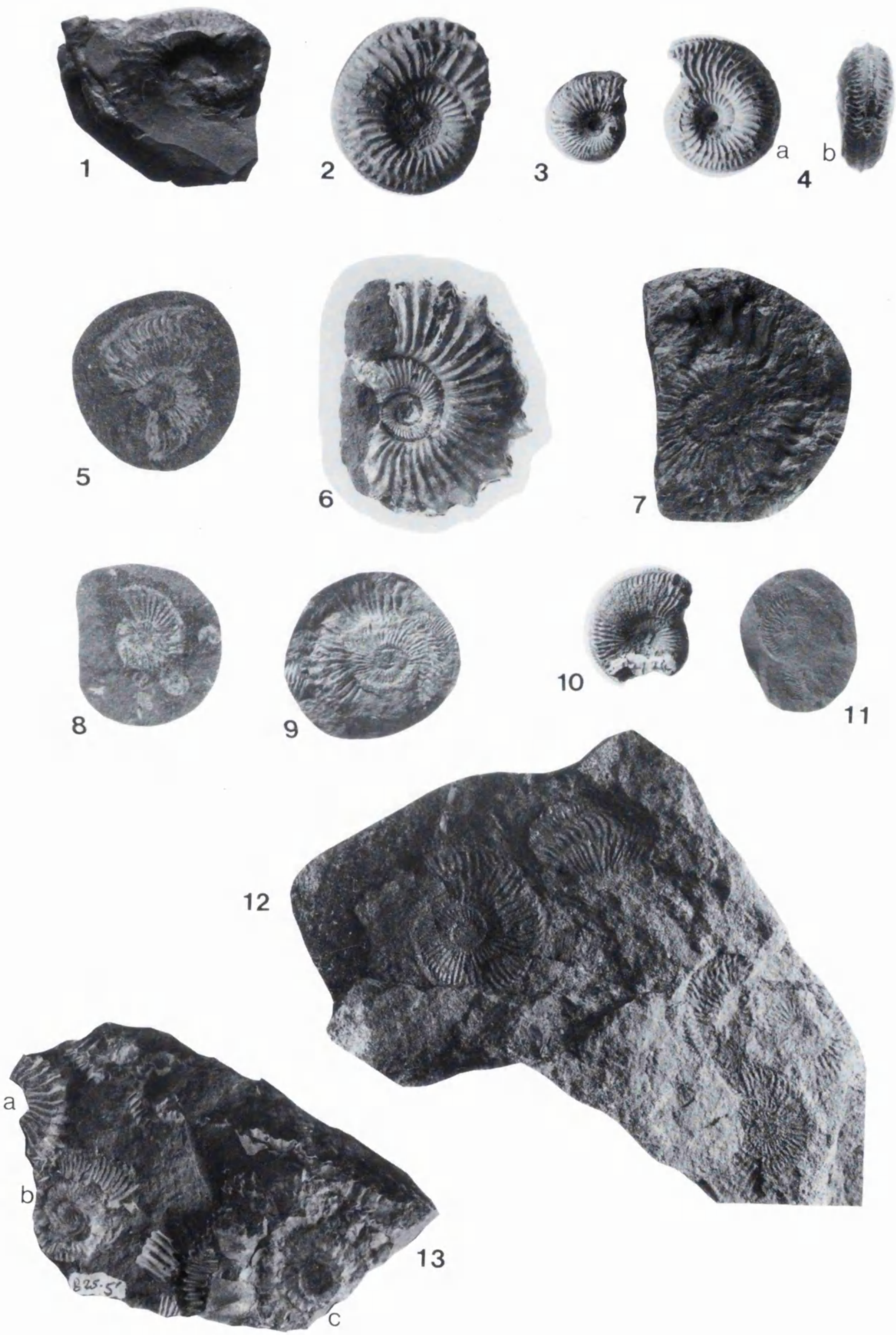

PLATE 4

PLATE 5

Amoeboceras (Euprionoceras) ***kochi*** Spath

Fig. 1. West Garty B28/8

Fig. 2a. 15/21a-25 8184'

2b. *Aulcostephanoides (Aulacostephanites) eulepidus* (Schneid) [see also Pl.6, Figs. 9, 10.]

Pictonia cf. ***densicostata*** Buckman

Fig. 3. South Ferriby 88.5.19/18 Bed 14

Prorasenia bowerbanki Spath

Fig. 4. South Ferriby 88.5.20/14 Bed 10

Prorasenia aff. ***triplicata*** (Sowerby)

Fig. 5. South Ferriby 88.5.18/2 Bed 18

Prorasenia spp.

Fig. 6a. South Ferriby 90.7.27/3

b. South Ferriby 88.5.18/3

c. South Ferriby 90.7.27/4

Prorasenia ? *bowerbanki* Spath.

Fig. 7a. South Ferriby 88.5.20/15

b. South Ferriby 88.5.19/2

Fig. 8a, b. South Ferriby 88.5.18/4

Prorasenia ? *triplicata* (Sowerby)

Fig. 9a. South Ferriby 88.5.19/24

b. South Ferriby 90.7.27/5

Fig. 10a, b. South Ferriby 90.7.27/6

Rasenia sp. cf. ***inconstans*** Spath

Fig. 11. 15/21a-4 8080'6"

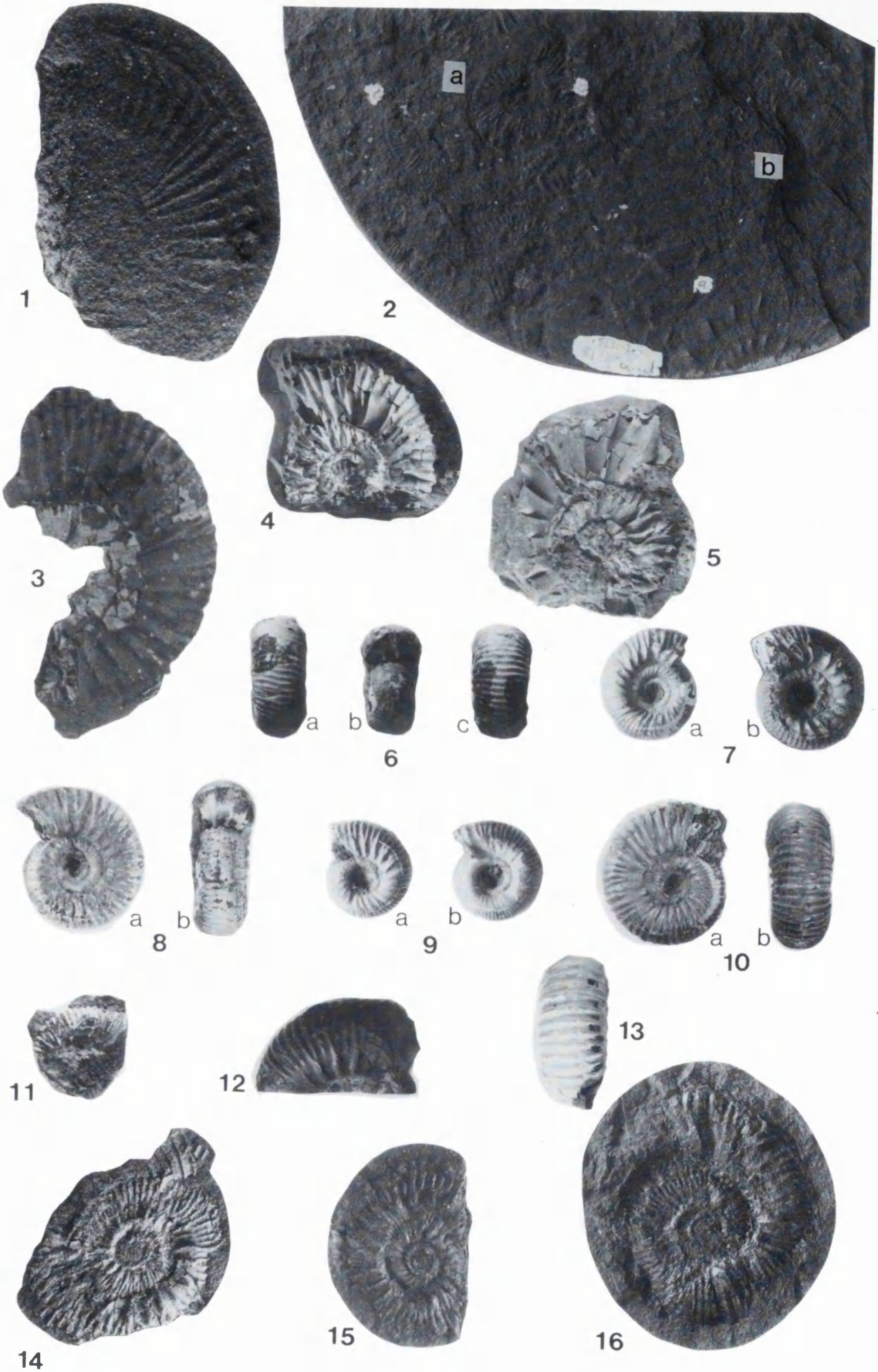

PLATE 5

Rasenia involuta Spath

Fig. 12. 15/22-5 14882'3"

Rasenia evoluta Spath

Fig. 13. 15/21a-12a 7929'7"

Fig. 14. Kintradwell B23/19

Fig. 15. Kintradwell B24/1

Rasenia sp. cf. *coronata* Mesezhnikov

Fig. 16. 15/21a-29 8660'6"

Figs. 6-11, 13, 16 magnification x1.5; others natural size.

PLATE 6

Fig. 1. Eathie B25/7 Casts.

a. *Amoeboceras (Amoebites) rasenense* Spath

b, c. *Rasenia (Rasenioides) möschi* (Oppel)

d, e. *Rasenia (Rasenioides) lepidula* (Oppel)

Rasenia (Rasenioides) lepidula (Oppel)

Fig. 2. Eathie B25/19 (with *A. (A.)* cf. *rasenense*)

Rasenia (Rasenioides) thermarum (Oppel)

Fig. 3. 15/21a-12a 7927'9-10"

Rasenia (Rasenioides) askepta Ziegler

Fig. 4. Eathie B25/6

Fig. 5a, b; Fig. 6. 15/21a-25 8384'

Aulacostephanoides (Aulacostephanoides) mutabilis (Sowerby)

Fig. 7. Crackaig Links B27/24

Aulacostephanoides sp. aff. ***mutabilis*** (Sowerby)

Fig. 8. 15/21a-11 7850'a ?7856' (see Fig. 3.10)

Aulacostephanoides (Aulacostephanites) eulepidus (Schneid)

Fig. 9. 15/21a-12a 7888'3"

Fig. 10. Crackaig Links B26/7

Aulacostephanoides (Aulacostephanites) cf. ***desmonotus*** (Oppel)

Fig. 11. Crackaig Links B27/17

Aulacostephanoides (Aulacostephanites) cf. ***linealis*** (Quenstedt)

Fig. 12. Crackaig Links B27/19

Fig. 3. magnification x2; others natural size.

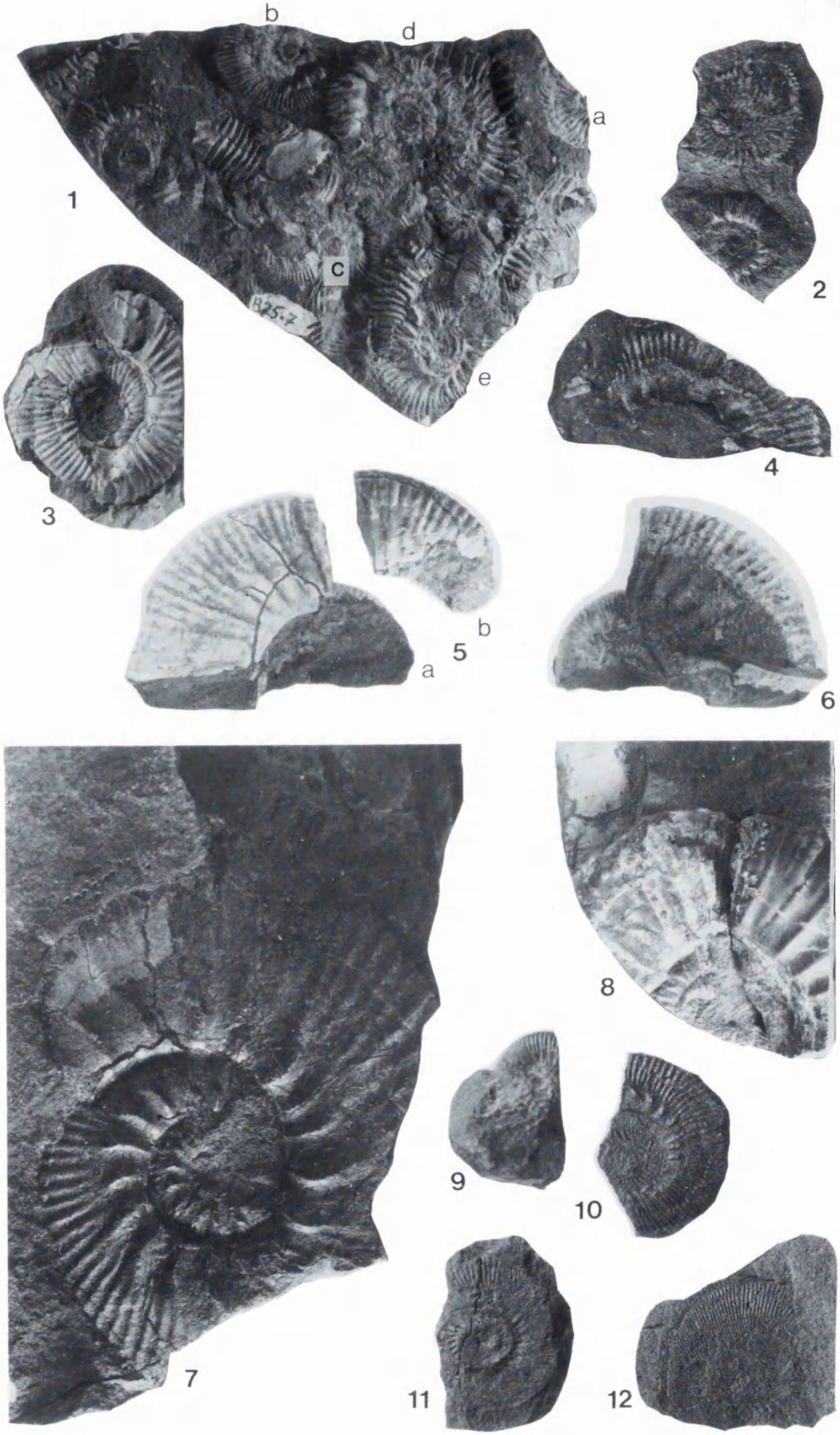

PLATE 6

PLATE 7

Aulacostephanus (Xenostephanoides) thurrelli Arkell & Callomon

Fig. 1. Crackaig Links B26/13

Fig. 2. 15/21a-11 7850'b ?7856' (see fig. 3.10)

Fig. 3. 15/21a-25 8386'9"

Aulacostephanus (Xenostephanoides) cf. *lindensis* Arkell & Callomon

Fig. 4. 15/22-5 14830'6"

Aulacostephanus (Aulacostephanoceras) cf. *eudoxus* (d'Orbigny)

Fig. 5. West Garty B28/3

Aulacostephanus sp. cf. *yo* (d'Orbigny)

Fig. 6. 15/21a-25 8176'5"

*

Fig. 7. Eathie B25/5 Moulds. (see also Pl. 4, Fig. 13)

a, b. *Amoeboceras (Amoebites) rasenense* Spath

c. *Rasenia (Rasenioides) lepidula* (Oppel)

d. *Rasenia (Rasenioides) askepta* Ziegler

Fig. 3 magnification x2; Fig. 4 x1.5; others natural size.

Fig. 5 cf. Amoeboceras (Hoplocardioceras) decipiens

Spath, 1935, pl. 2, figs. 1, 2; pl.3, fig. 2 (H); pl. 4, fig. 7.

Fig. 6. cf. Aulacostephanoides (Aulacostephanites) linealis

(Quenstedt) in Ziegler, 1962, pl. 2, figs. 1-10

cf. Aulacostephanoides (Aulacostephanites) desmonotus

(Oppel) in Ziegler, 1962, pl. 2, figs. 13-15

PLATE 7

Appendix #1 - BOLDY, S.A.R. & BREALEY, S.J.
Timing, nature and sedimentary result of Jurassic tectonism in the Outer Moray Firth.

Timing, nature and sedimentary result of Jurassic tectonism in the Outer Moray Firth

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Abstract: Jurassic sedimentation in the Outer Moray Firth took place under a changing tectonic regime, accompanied by regional transgression in the late Jurassic. An early phase of tectonism is recognised, accompanying the collapse of the Central North Sea Dome. This Mid-Cimmerian phase of tectonism is characterized by North–South, Viking trend, faults and reactivated Northeast–Southwest Caledonian faults. These predominantly Bathonian age faults controlled subsidence and deposition of the Middle Jurassic Rattray Volcanics Formation. The Rattray Volcanics are unconformably overlain by the Sgiath and Piper Formations, of Oxfordian to early Kimmeridgian age, deposits of a northward prograding delta that continued to be affected by movement on Mid-Cimmerian faults.

A dramatic change in tectonic regime occurred during the Kimmeridgian, possibly concurrent with the major Eudoxus Zone transgression, that heralded the onset of Kimmeridge Clay deposition. During this Late Cimmerian rift-phase, sedimentation took place under conditions of active extension controlled by northwest–southeast, Witch Ground Graben trend, faults. The Kimmeridge Clay Formation is a typical syn-rift sequence with sands deposited on the downthrown sides of rotational fault blocks, whose crests were commonly eroded. Studies of ammonites recovered from cored sequences have refined the interpretation of timing of tectonic and transgressive events and have also highlighted anomalies in correlation between ammonite and dinocyst zonation schemes.

The Moray Firth Basin is the term given to the complex series of fault blocks and grabens, which displays overall east–west trend, extending offshore from the Moray Firth (Fig. 1). This basinal area has commonly been considered to form the third arm of a trilete rift system or triple junction (Whiteman *et al.* 1975; Woodhall & Knox 1979; Ziegler 1981), the other rift axes being the Viking and Central Grabens (Fig. 1).

On the basis of structural style and stratigraphical succession, the overall Moray Firth Basin is sub-divided into an Inner and an Outer Basin, across an axis that trends north–south through the central part of Quadrant 13 (Barr 1985). The stratigraphy, tectonic evolution and palaeogeography have been well documented in a number of recent papers (Turner *et al.* 1984, Andrews & Brown 1987, Harker *et al.* 1987 and Boote & Gustav 1987).

Exploration in the Outer Moray Firth has resulted in the delineation of a number of major oil fields, the principal ones being Piper, Claymore, Tartan and Scott. The most important reservoir rocks occur in the Upper Jurassic, in the shallow-marine to deltaic Piper Sands and in the deeper water submarine-fan Claymore Sands. Total recoverable reserves anticipated from fields in production and under development amount to 1.93 billion barrels (Department of Energy 1989), highlighting the economic importance of the Outer Moray Firth.

This paper presents the results of regional and detailed stratigraphical and structural evaluation carried out during the exploration and appraisal of Block 15/21 where two fields, Ivanhoe and Rob Roy have recently entered production. Both these fields produce from Upper Jurassic Piper Sandstone reservoirs. A further major field has recently been delineated in the eastern part of Block 15/21; it extends into Block 15/22 and has been named Scott.

The results of these studies have been to record an important change in tectonic activity during the Jurassic. During Bathonian to Early Kimmeridgian times, northeast–southwest trending Caledonian faults and north–south Mid-Cimmerian 'Viking' trending faults were dominant, exerting a strong control on isopach patterns. However, during the Kimmeridgian a change in the dominant fault trend occurred and northwest–southeast faulting controlled isopach patterns. These faults parallel the major structural feature in the Outer Moray Firth, the Witch Ground Graben and are therefore termed 'Witch Ground' trend. These faults were formed in response to Late Cimmerian rifting which was the major phase of extensional tectonism affecting the Outer Moray Firth.

From HARDMAN, R. F. P. & BROOKS, J. (eds), 1990, *Tectonic Events Responsible for Britain's Oil and Gas Reserves*, Geological Society Special Publication No 55, pp 259–279.

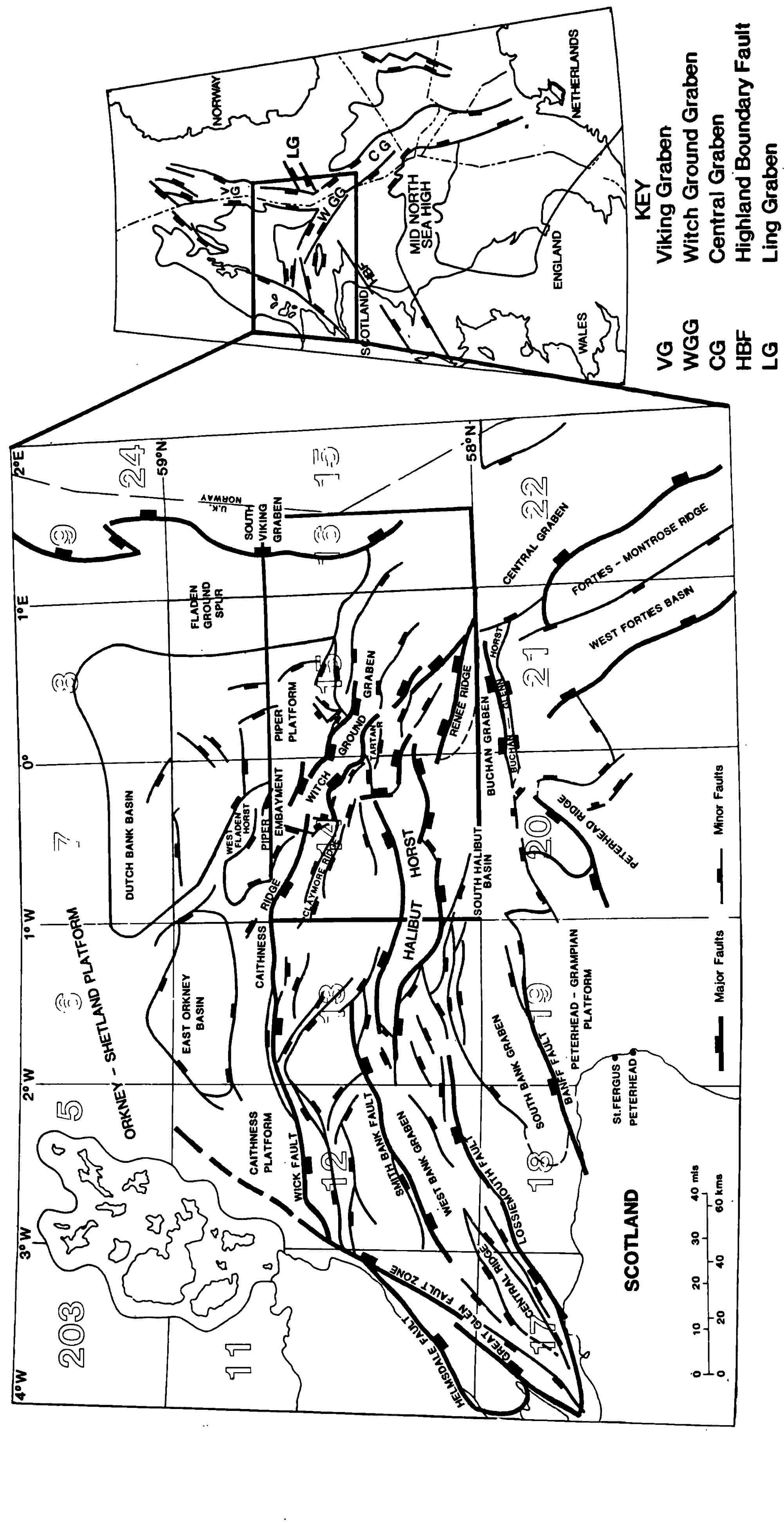

Fig. 1. Moray Firth: regional structural elements.

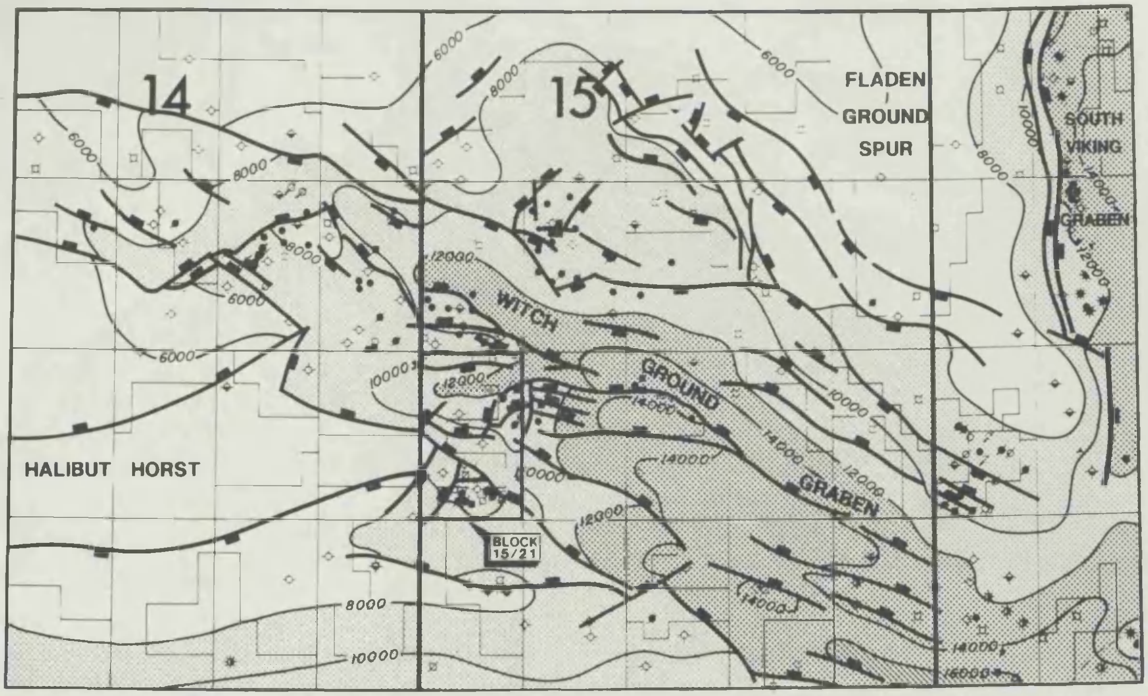

Fig. 2. Outer Moray Firth: depth structure map at base Cretaceous, highlighting major structural elements. Depth contours in feet subsea.

Ammonites recovered from cored sequences in wells in Block 15/21 provide detailed biostratigraphical zonation and allow the relationship between tectonic movements and sedimentary response to be documented more clearly.

Regional structural elements and pre-Jurassic stratigraphy

The regional structural elements map of the Moray Firth (Fig. 1) and the more local structure map at Base Cretaceous of the Outer Moray Firth area (Fig. 2), highlight the interaction of a number of fault trends.

Caledonian basement

Caledonian faults trend northeast-southwest and the principal faults are the Great Glen Fault Zone and the Highland Boundary Fault. The Great Glen Fault Zone has had a complex post-Caledonian history (Rogers *et al.* 1989) and has played a part in basin formation in the Inner Moray Firth from Devonian to Cretaceous times.

The Highland Boundary Fault System can be traced offshore in a northeastward direction to the northeast–southwest trending Ling Graben in the Norwegian sector (Doré & Gage 1987). This lineation, which has been postulated to represent a major crustal discontinuity (Doré & Gage 1987), marks the southern boundary of the Outer Moray Firth province.

The structure map at Base Cretaceous level (Fig. 2) shows that a number of northeast–southwest Caledonian trend faults traverse the Outer Moray Firth, and have influenced basin development in the Mesozoic. One prominent fault set along this trend traverses the Claymore Field in Block 14/19 and parallel faults have also been documented in the Piper Field (Maher 1980) and in Block 15/21.

Upper Palaeozoic sedimentation and Hercynian tectonism

The Moray Firth is underlain by a major Devonian basin, believed to have been initiated by transtensional movement along the Great Glen Fault Zone (McQuillin *et al.* 1982; Rogers *et al.* 1989). Within this basin, thick sequences of continental clastics accumulated. In the Outer Moray Firth, the Devonian is succeeded by Lower Carboniferous strata (Harker *et al.* 1987), believed to have been deposited during an extensional tectonic regime (Leeder & Boldy 1990), similar to that described in other North British Basins (Leeder 1982, 1987). An east–west orientation of the Outer Moray Firth Carboniferous Basin is suggested by the pre-Mesozoic sub-crop and isopach pattern and this is parallel to other well documented Carboniferous basins such as the Northumberland–Solway Basin.

It is likely that major east-west faults were initiated during this Upper Palaeozoic extensional phase and faults of this trend include the Wick Fault and the faults bounding the Halibut Horst. However, the Hercynian Orogeny, with its overall north–south compression, resulted in widespread uplift and erosion of the Outer Moray Firth area.

Early Cimmerian tectonism

There is a regional unconformity in the Outer Moray Firth between the Carboniferous of Dinantian age, and overlying Permian strata (Fig. 3). The Rotliegend is only locally developed, but Zechstein carbonates and evaporites are widespread. Triassic strata conformably overlie the Zechstein and consist of red siltstones and shales of the Smith Bank Formation, overlain in the western part of the Outer Moray Firth by more arenaceous sequences of the Skagerrak Formation (Fig. 3).

It is difficult to discern any evidence during the Permo-Triassic depositional episode of active fault control on sedimentation. It appears more likely that deposition under conditions of regional subsidence took place with the sinking of a basement composed of Caledonian and Upper Palaeozoic rocks, melded during the Hercynian Orogeny.

Jurassic sedimentation and tectonics

Episode 1: Mid-Cimmerian tectonism and Mid-Jurassic deposition

Throughout the Outer Moray Firth area there is an unconformity between Jurassic Strata and the underlying Triassic or older section. The oldest Jurassic rocks present are the volcanic sequences of the Rattray Volcanic Formation and the time-equivalent paralic sediments of the Pentland Formation (Fig. 3). These two formations are together classified as the Fladen Group (Deegan & Scull 1977).

Dating of the volcanics has indicated ages no older than Bajocian, with most dating indicating a Bathonian age (Howitt *et al.* 1975). Recent work using Ar/Ar dating on intrusives and volcanics has yielded an age of 153 ± 4 Ma, within the Callovian (Ritchie *et al.* 1988). However, biostratigraphical analysis of Pentland Formation sequences and of sediments interbedded with the volcanics of the Rattray Formation, supports a Bathonian age.

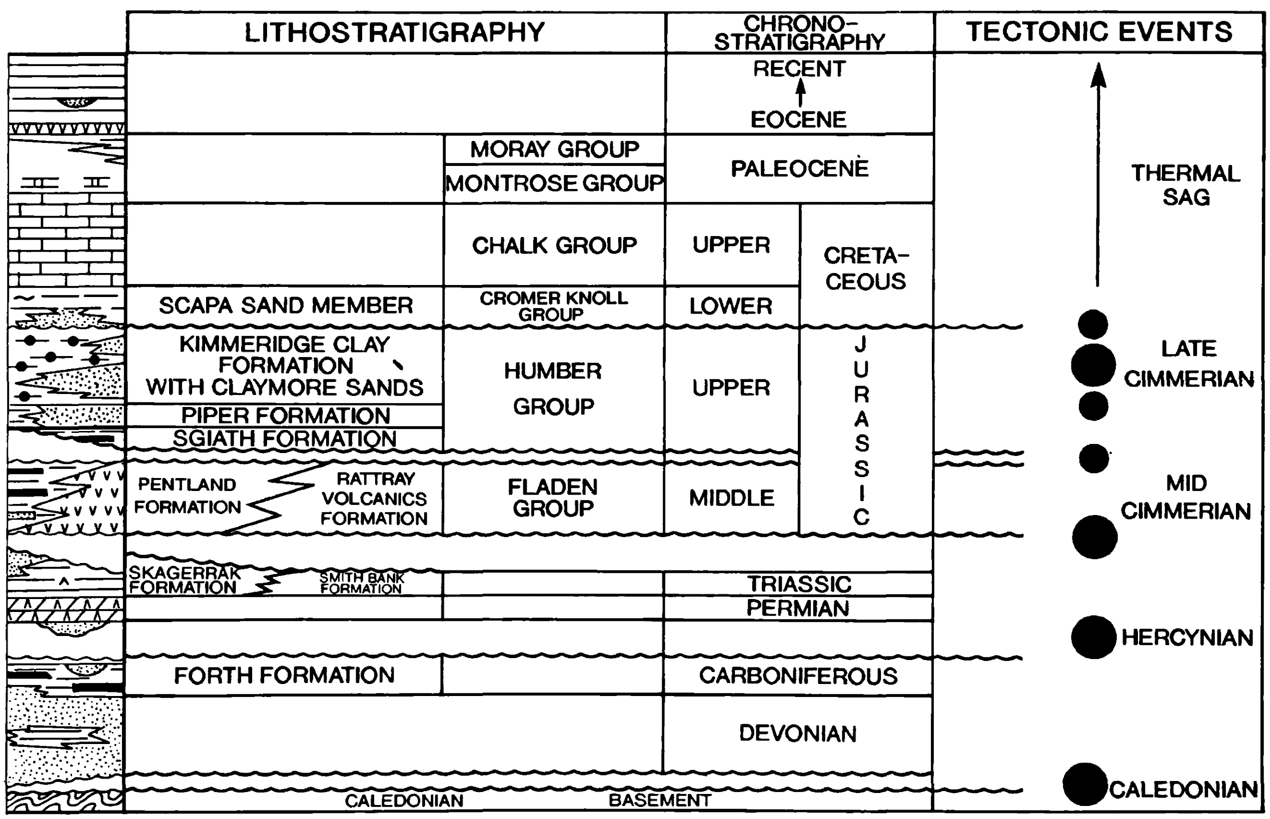

Fig. 3. Outer Moray Firth: stratigraphic column.

There are therefore no early Jurassic sediments known to be preserved in the Outer Moray Firth and this has been attributed to their removal during the pre-rift updoming of the Central North Sea area (Eynon 1981). Elsewhere, within the North Sea and throughout much of North West Europe, the early Jurassic records an important transgressive pulse, drowning the low-lying Triassic hinterland and leading to the deposition of shallow marine clastics. It is impossible to decipher the extent of early Jurassic deposition within the Outer Moray Firth, but it is generally agreed that the onset of uplift did not occur until the Aalenian to Toarcian (Eynon 1981).

The uplift and subsequent collapse of the Central North Sea Dome are the response in the Outer Moray Firth to a widespread tectonic event, generally termed the Mid-Cimmerian. The volcanics and sedimentary sequences of the Fladen Group were deposited during extensional rifting, associated with collapse of the dome. An isochore map of this sequence in the Outer Moray Firth (Fig. 4) displays a strong north–south pattern, which is attributed to control by north–south and northeast–southwest faults. These faults are termed the 'Viking' trend as they parallel the faults that control the Viking Graben system to the east.

Also apparent from the isochore map, is the absence of the Middle Jurassic Fladen Group in the western part of the Outer Moray Firth in Quadrant 14 and to the east, where the Middle Jurassic strata overstep the Triassic and Zechstein to onlap the Fladen Ground Spur, which acted as a major positive structure throughout the Jurassic. It seems likely that a positive north–south fault block, similar to the Fladen Ground Spur, extended through Quadrant 14, but the effects of later tectonism obscure this relationship.

The thickest sequences of the Fladen Group

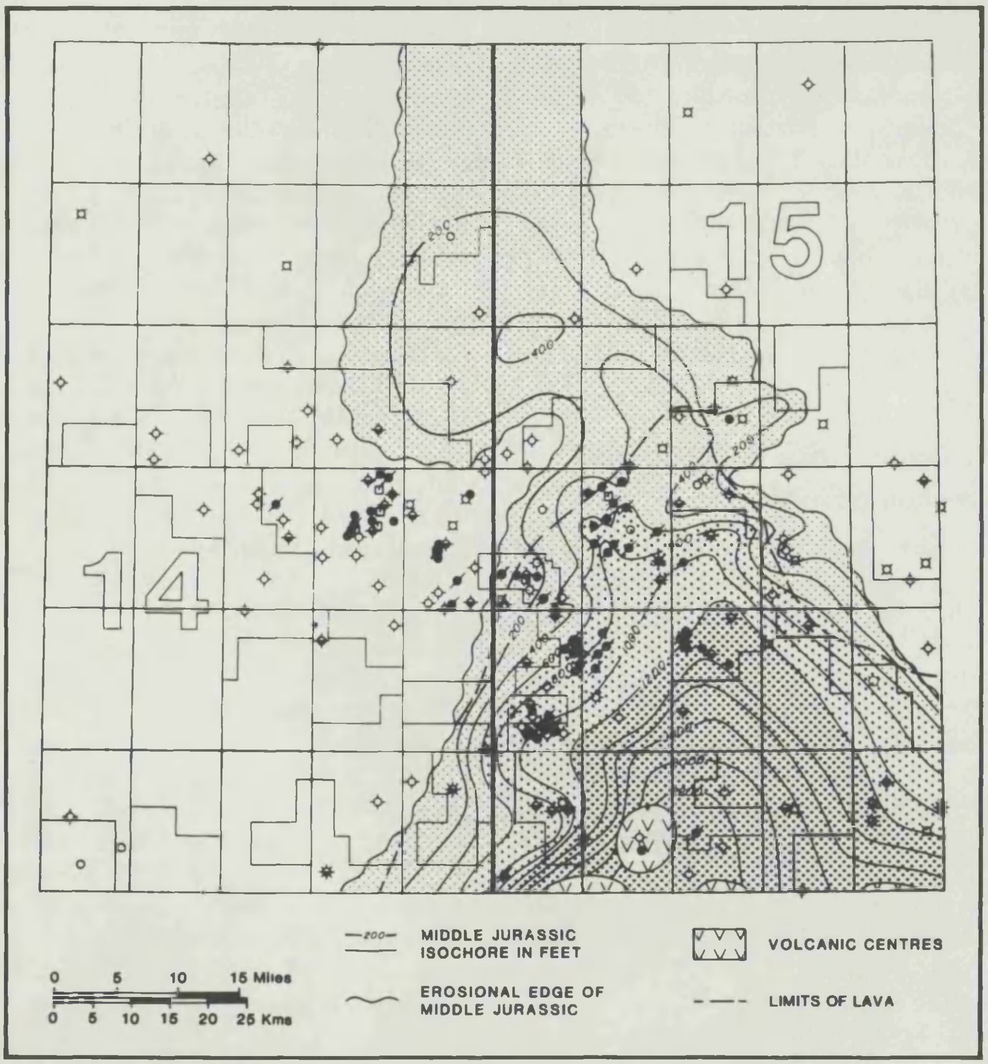

Fig. 4. Quadrants 14 and 15: Middle Jurassic Fladen Group distribution and thickness.

occur in the southern part of the Outer Moray Firth, in the south of Quadrant 15, where several volcanic vents have been postulated on geophysical evidence (Howitt *et al.* 1975). Several wells have proven thicknesses of volcanics of 1000 to 2000 ft; whilst the thickest recorded section occurs in the 15/27−2 well, which terminated having drilled 3691 ft of volcanics. Woodhall & Knox (1979) have suggested, from interpretation of marine magnetic data, that thicknesses in excess of 10000 ft may occur in the southern part of Quadrant 15.

Although locally extremely thick, the Middle Jurassic volcanics are restricted areally to the junction between the Outer Moray Firth, South Viking Graben and Central Graben. The location of the volcanics at the junction of these three basins has lead to speculation that this represents a plume generated triple junction (Whiteman *et al.* 1975; Woodhall & Knox 1979; Ziegler 1981), of the type described by Burke & Dewey (1974). However, the triple junction geometry consists of a combination of north-south 'Viking' Trend structures, younger WNW−ESE 'Witch Ground' Trend structures and northwest-southeast trending structures of the Central Graben that postdate the Middle Jurassic Volcanics. Furthermore, Latin *et al.* (this volume) have shown that the geochemistry of the Middle Jurassic Volcanics indicates that if they result from melting of normal aesthenosphere (i.e. that which produces MORB, Mid-Ocean Ridge Basalt), then only a small degree of melting has taken place which may be incompatible with a mantle plume origin.

Episode 2: Upper Jurassic: Sgiath and Piper Formation deposition

The oldest sediments overlying the Middle Jurassic Fladen Group in the Outer Moray Firth are the paralic coal-bearing sequences assigned to the Sgiath Formation by Harker *et al.* (1987) and these are considered to be no older than Mid-Oxfordian (Harker *et al.* 1987). There is therefore a significant unconformity and period of non-deposition between the Bathonian−?Callovian Fladen Group and the overlying Sgiath Formation of Upper Jurassic age (Fig. 3).

The Upper Jurassic was a period of progressive rise in sea level (Vail & Todd 1981; Rawson & Riley 1982; Haq *et al.* 1987) and this is recorded in the sedimentary succession in the Outer Moray Firth, with basal paralics of the Sgiath Formation passing upward into the shallow marine/shoreface sequences of the Piper Formation, which in turn are succeeded by deeper marine organic shales of the Kimmeridge Clay Formation.

The Upper Jurassic strata can be subdivided into two sequences (Fig. 3). An early, essentially pre-rift sequence, comprises the Sgiath and Piper Formations, whose isopach pattern mirrors that of the preceding Middle Jurassic and thus relates to the dying effects of Mid-Cimmerian tectonism. The Kimmeridge Clay Formation displays a different isochore pattern, with much more rapid thickness variation. The Kimmeridge Clay Formation forms the first part of the Late Cimmerian syn-rift sequence, that also includes Lower Cretaceous strata; these were deposited during the major phase of extension affecting the Outer Moray Firth.

The isochore map for the combined Sgiath and Piper Formations (Fig. 5) displays an overall north-south control with the major depocentre trending along the junction between Quadrants 14 and 15. This pattern is attributed to movement on syndepositional north−south 'Viking' trend faults. One of the thickest sequences of Sgiath and Piper drilled to date occurs in the 15/21−2 well where some 1285 ft of section was drilled, with the well terminating within the Sgiath Formation.

The combined Sgiath/Piper interval thins eastwards onto the Fladen Ground Spur. This may reflect a combination of both depositional thinning and later erosional truncation. The Piper and Sgiath Formations are absent in the west, over much of Quadrant 14 and over the Halibut Horst. It is considered likely that the Halibut Horst was originally covered by sequences of Sgiath and Piper but these have been subsequently eroded, yielding abundant clastic supply to the Witch Ground Graben during the Late Cimmerian extension, with the Piper Sands being reworked into the Claymore Member Sands of the Kimmeridge Clay Formation.

Overprinted upon the north-south depositional control of the Piper−Sgiath isochore pattern are the effects of Late Cimmerian extensional tectonism. Many of the tilted fault block structures of the Outer Moray Firth display erosion of the Sgiath and Piper Formations from the crestal parts of fault blocks formed by west−northwest trending (Witch Ground) normal faults. Such crestal erosion has been documented from the Claymore Field (Maher & Harker 1987) and Piper Field (Maher 1980), and also occurs in the Rob Roy and Galley Fields.

In summary, although there was activity on north−south Viking Trend faults during the

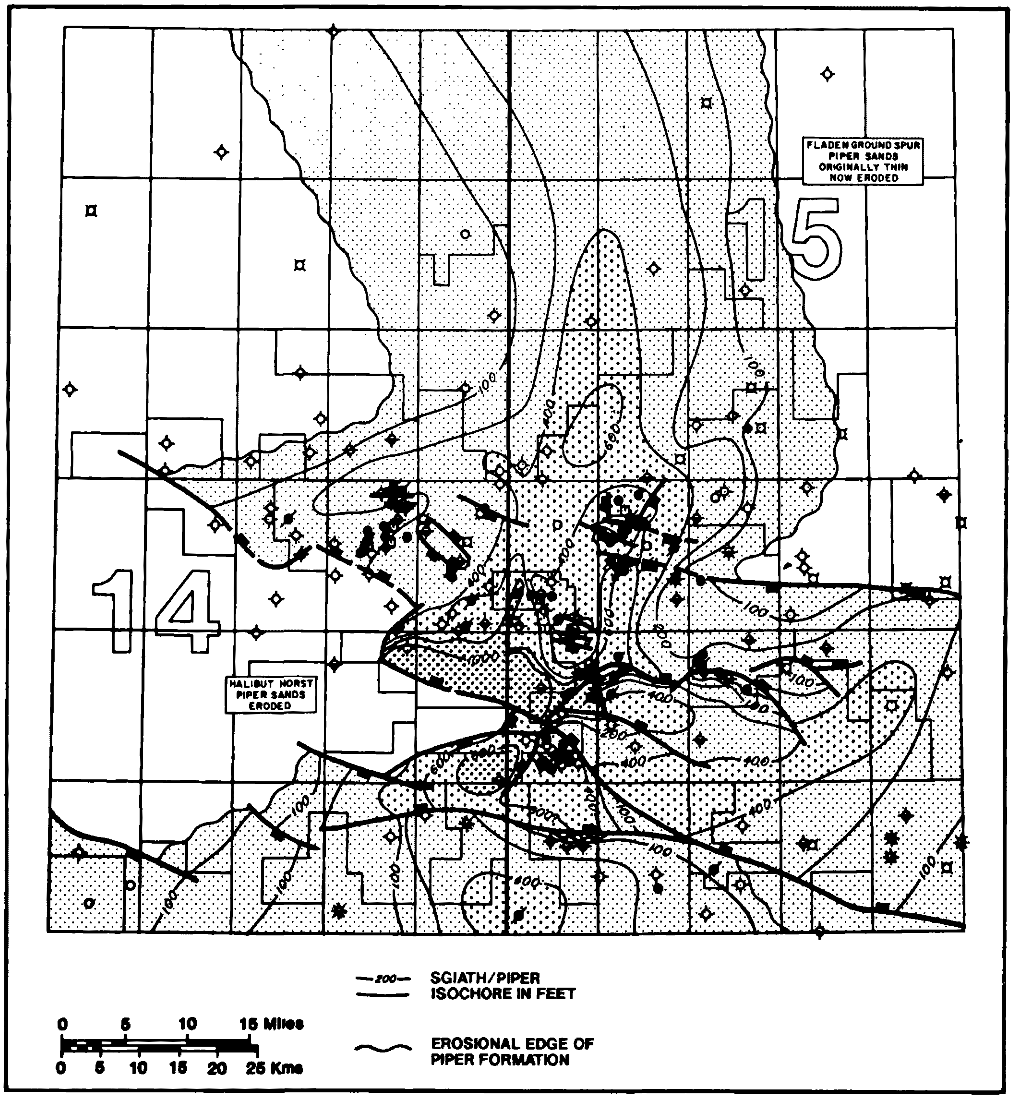

Fig. 5. Quadrants 14 and 15: Upper Jurassic Sgiath and Piper Formations distribution and thickness.

deposition of the Sgiath and Piper Formation, these sequences were deposited during the late stages of Mid-Cimmerian tectonism and can be considered as a pre-rift succession to the succeeding Late Cimmerian syn-rift sequence.

Episode 3: Upper Jurassic: Kimmeridge Clay Formation deposition

The regional isochore map of the Kimmeridge Clay Formation (Fig. 6), displays clearly the change in subsidence and sedimentation patterns associated with the opening of the Witch Ground Graben. Faults defining the graben are oriented WNW–ESE and the isochore pattern is parallel to these faults.

The Kimmeridge Clay Formation, of Kimmeridgian to early Ryazanian age (Harker *et al.* 1987), consists of typical organically rich black shales, but also contains several significant sandstone units, deposited by mass flow mechanisms down fault controlled palaeoslopes. The Claymore Sand Member of the Claymore Field is the only one of these sand units to have been formally defined and until the lithostratigraphical nomenclature is formalized further, all sands within the Kimmeridge Clay Formation are referred to here as Claymore Sands, although they are not all of the same age as those seen in the Claymore Field.

The isochore map of the Kimmeridge Clay Formation (Fig. 6) displays great variability over short distances, reflecting the strong tectonic control on this syn-rift sequence. In the deepest parts of the Witch Ground Graben thicknesses in excess of 3000 ft have been proven by drilling. However, there are a number of positive tectonic features over which the Kimmeridge Clay is absent. In the eastern part of Quadrant 15, the Fladen Ground Spur continued as a high area during Kimmeridge Clay

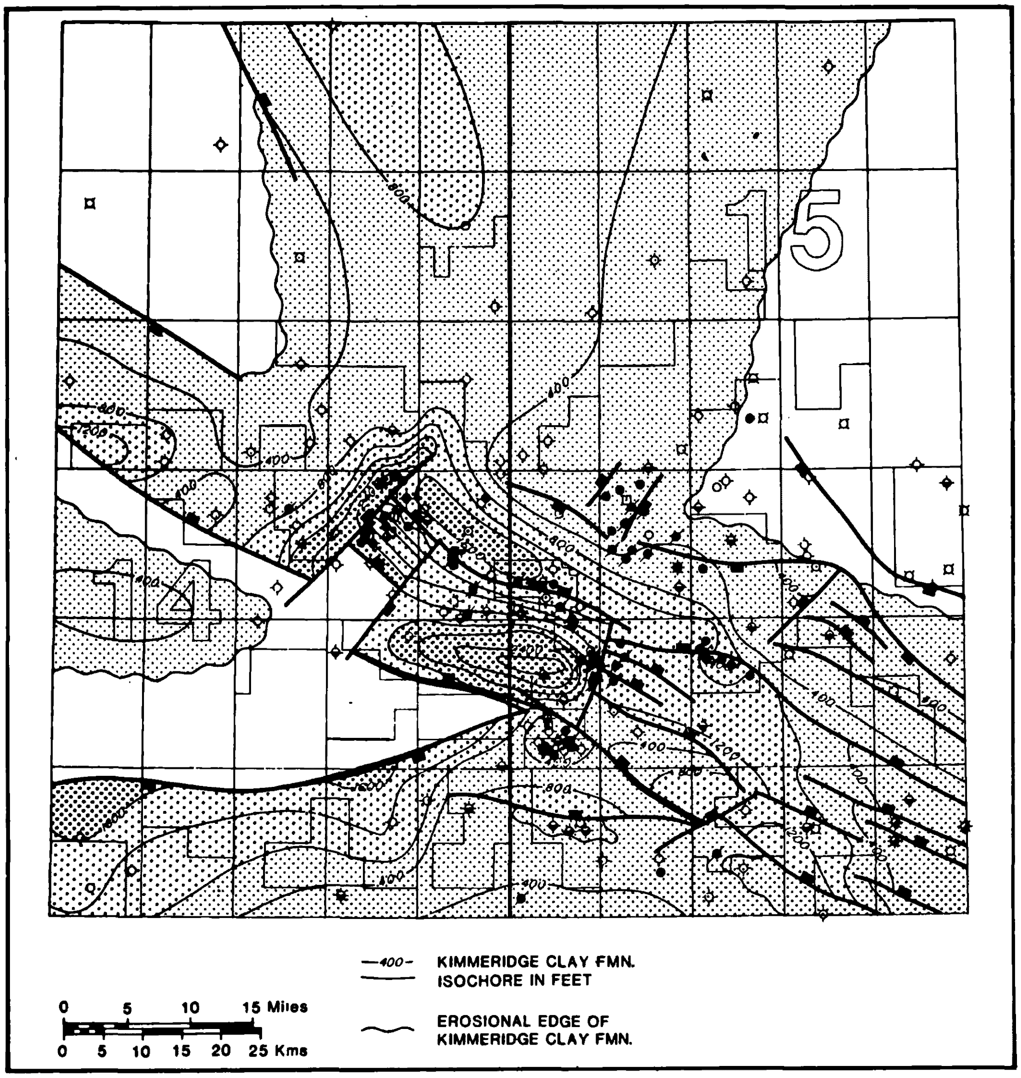

Fig. 6. Quadrants 14 and 15: Upper Jurassic Kimmeridge Clay Formation distribution and thickness.

deposition and the absence of Kimmeridge Clay here may be a function of both non-deposition and later erosion. A similar scenario can be envisaged for the Halibut Horst which is interpreted to have emerged as a positive block during Kimmeridge Clay times and undergone intense erosion, shedding coarse clastics to form the Claymore Sands. The mineralogical maturity of the Claymore Sands suggests strongly that they represent redeposition of Piper Sands, eroded from areas such as the Halibut Horst and other intrabasinal fault blocks.

Within the Witch Ground Graben itself, the variation in thickness of the Kimmeridge Clay Formation (Fig. 6) reflects the infilling of the tilted fault block topography that was formed by Late Cimmerian extensional tectonics. Well data from Block 15/21 has shown that there is often a hiatus above the Piper Formation, with a considerable part of the earliest Kimmeridge Clay Formation absent. This marks the onset of Late Cimmerian tectonics and is dated to be within the Kimmeridgian, probably occurring within the Eudoxus Zone.

Jurassic tectonics and sedimentation in block 15/21

Structural elements

The major structural elements in Block 15/21 are shown in Fig. 7. This structural configuration has been delineated utilizing a very extensive database, comprising two 3D seismic surveys, several 2D seismic datasets and 25 exploration and appraisal wells.

The southern flank of the Tartan Ridge extends in a east–west direction across the northernmost part of Block 15/21. The other major positive structural feature is the Halibut Horst Spur (Fig. 7). The Halibut Horst itself is a very

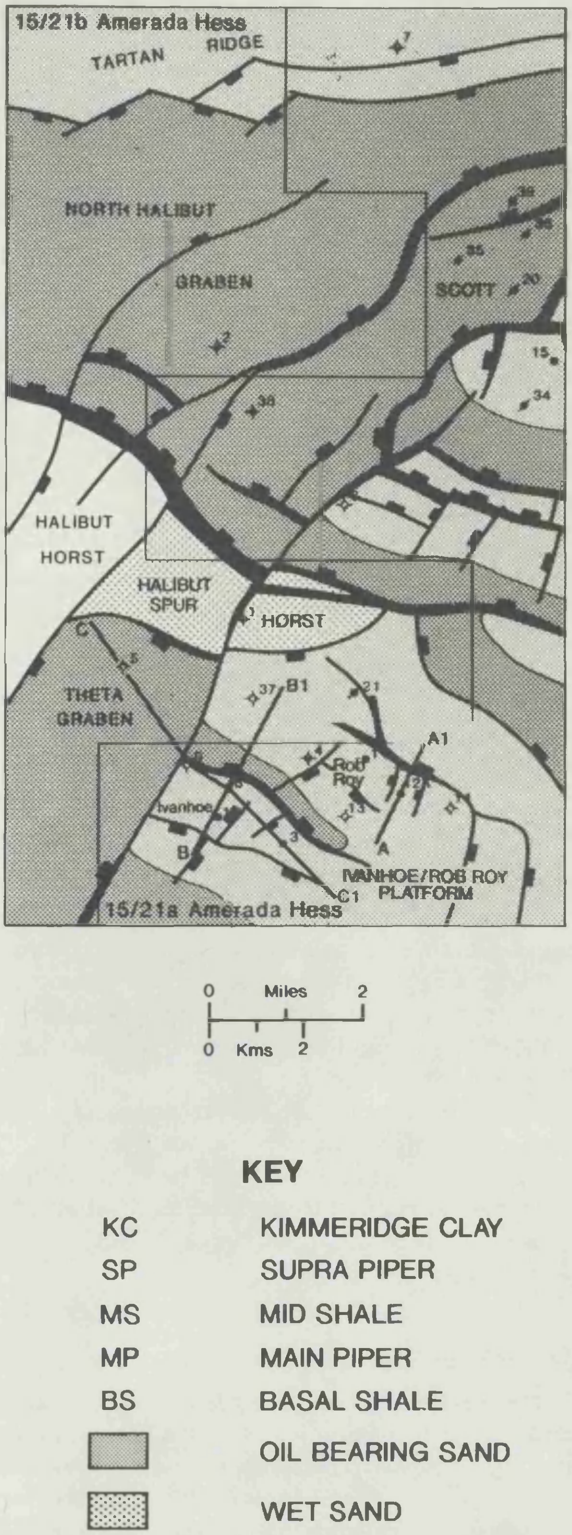

Fig. 7. Block 15/21: Structural Elements. Location of structural sections illustrated in Figs 12, 13 & 15 are annotated A–A[1], B–B[1] and C–C[1] respectively.

shallow feature with little or no Mesozoic section preserved, whilst the Halibut Horst Spur retains some Jurassic section, albeit severely truncated.

In the southernmost part of Block 15/21 the Ivanhoe and Rob Roy Fields lie in an area of intermediate structural relief termed the Ivanhoe/Rob Roy Platform (Fig. 7).

Two grabens traverse Block 15/21 and these reflect the two different fault trends recognised in the regional review. A graben bounded by northeasterly trending faults separates the Halibut Horst from the Ivanhoe/Rob Roy Platform (Fig. 7) and this feature is termed the Theta Graben. It is defined most clearly in the southern part of block 15/21, but continues at depth to the northeast, where it interacts with a graben traversing the northern half of Block 15/21 that is defined by east–west and northwest–southeast faults of the Witch Ground trend. This graben, called the North Halibut Graben, separates the Tartan Ridge to the north, from the Halibut Horst, to the South (Fig. 7).

Jurassic lithostratigraphy

The Jurassic lithostratigraphic nomenclature utilized in Block 15/21 is shown in Fig. 8, against the electric logs from the 15/21a–11 Rob Roy discovery well. A major unconformity separates the Middle Jurassic Rattray Volcanics Formation of the Fladen Group, from the overlying Upper Jurassic Humber Group.

Historically, in Block 15/21 the Humber Group has been divided into two constituent formations: the Piper Formation and the overlying Kimmeridge Clay Formation. The Piper Formation was further subdivided into four members, from the base upward these are: the Basal Shale Member, Main Piper Sand Member, Mid-Shale Member and Supra Piper Sand Member.

However, Harker *et al.* (1987), has defined a new unit, the Sgiath Formation, as comprising a paralic sequence of sandstones, coals carbonaceous mudstones and siltstones. The top of the Sgiath Formation and base of the overlying Piper Formation is defined by the change in log character from low gamma ray sands to high gamma ray mudstones of the marine 'I' Shale (Harker *et al.* 1987).

Considerable uncertainty remains in correlating the 'I' shale from the type section in the Piper Field southwestward into Block 15/21. However, in Block 15/21 a tripartite division of the basal shale sequence into a Marine Unit, a Paralic Unit and a Coal Unit can readily be recognized (Fig. 8). The lower two units are assigned to the Sgiath Formation as they represent non-marine sedimentation. The Marine Shale Unit is considered to form the lowermost part of the Piper Formation and represents a

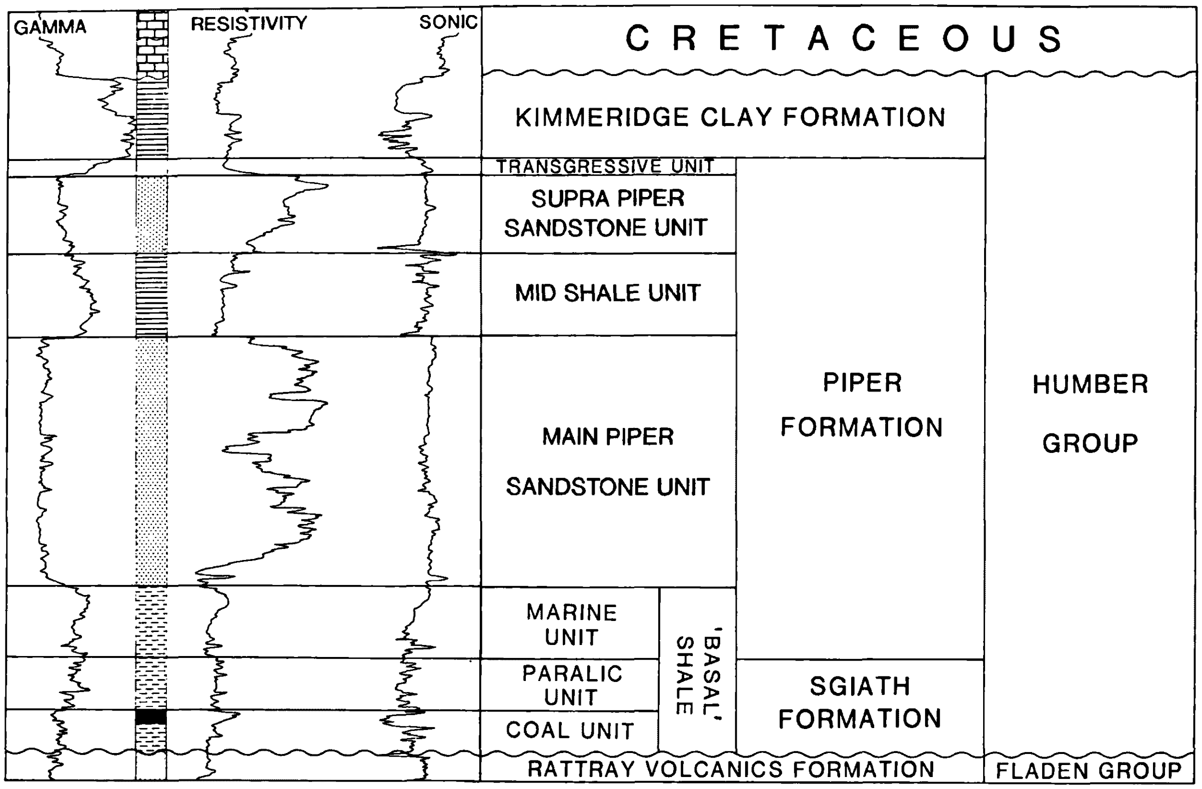

Fig. 8. Block 15/21: Jurassic lithostratigraphy.

major transgression which resulted in a fully marine depositional environment.

The Marine Shale Unit coarsens upward and passes gradationally into the overlying Main Piper Sandstone Unit (Fig. 8), which consists almost entirely of medium to coarse grained quartzose sandstones. Another major marine transgression terminated deposition of the Main Piper Sands and resulted in the accumulation of the Mid-Shale under fully marine conditions.

A second major coarsening-upward regressive sequence is recognized, with the Mid-Shale passing upwards into the Supra Piper Sandstone (Fig. 8). This is composed of medium-fine grained sandstones, significantly richer in detrital felspar grains in comparison to the Main Piper Sands.

The uppermost unit recognised within the Piper Formation is a thin fining-upward transgressive sequence. This is overlain by highly radioactive shales of the Kimmeridge Clay Formation (Fig. 8). There is a marked velocity contrast between the relatively low velocity organic shales of the Kimmeridge Clay formation and the higher velocity 'cold' shales of the Transgressive Unit of the Piper Formation. This contrast gives rise to a seismic event of variable intensity, but mappable over much of the area.

Furthermore, the boundary between the Kimmeridge Clay and Piper Formations is often a significant hiatus, with the oldest Kimmeridge Clay condensed or even absent altogether. The great variation in thickness of this early Kimmeridge Clay is strong evidence of significant faulting, concomittant with the major transgression that heralded the onset of Kimmeridge Clay deposition.

Lithologies within the Kimmeridge Clay Formation are highly variable within Block 15/21. In places it contains very thick sandstone sequences, assigned to the Claymore Member.

Tectonic controls on Sgiath and Piper Formation deposition

In the regional review of Jurassic sedimentation and tectonics, attention was drawn to the change in the isochore pattern between the north–south 'Viking' trend of the Middle Jurassic and Sgiath/Piper interval; and the northwest–southeast 'Witch Ground' Trend of the Kimmeridge Clay Formation (Figs 4, 5 & 6). This change in tectonic control is highlighted at a local level within Block 15/21 (Figs 9 & 10).

The isochore map for the combined Sgiath and Piper Formations has been composed using both well and seismic data. There is clear evidence of north–northeasterly trending depositional axes, the most pronounced of these being the Theta Graben, where a much thicker Sgiath/

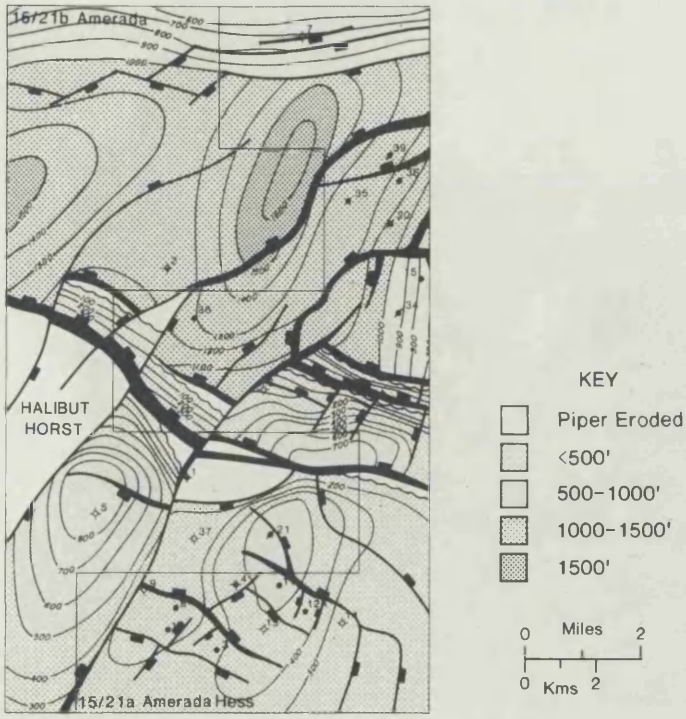

Fig. 9. Block 15/21: isochore map of Upper Jurassic Sgiath and Piper Formations.

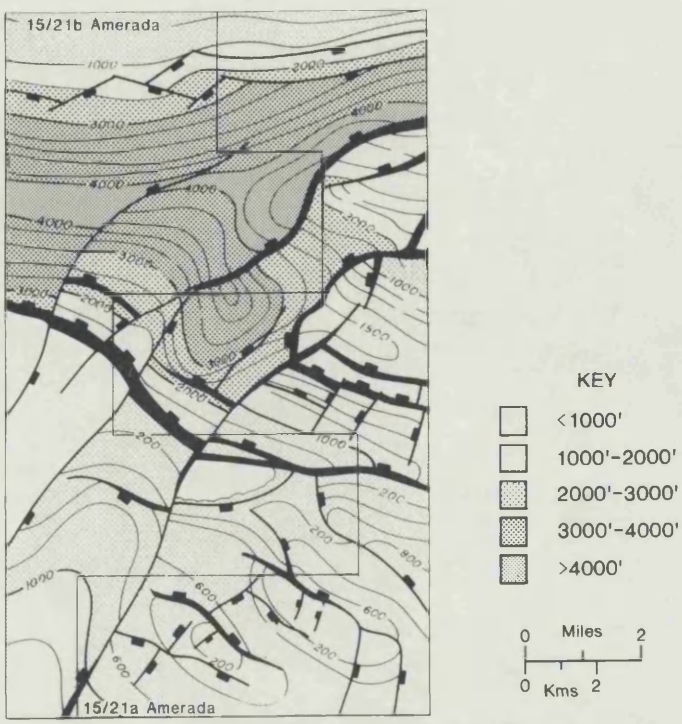

Fig. 10. Block 15/21: isochore map of Upper Jurassic Kimmeridge Clay Formation.

Piper sequence was penetrated in the 15/21–5 well (800 ft +) than is seen in wells on the Ivanhoe/Rob Roy Platform (Fig. 9). The maximum drilled thickness was encountered in the 15/21–2 well, where the combined Sgiath/Piper interval totals 1285 ft. Even thicker sequences are postulated within the northeasterly extension of the Theta Graben where up to 1600 ft may be present.

A parallel depositional axis is recognised trending north–northeasterly through the eastern part of Ivanhoe Field and the western part

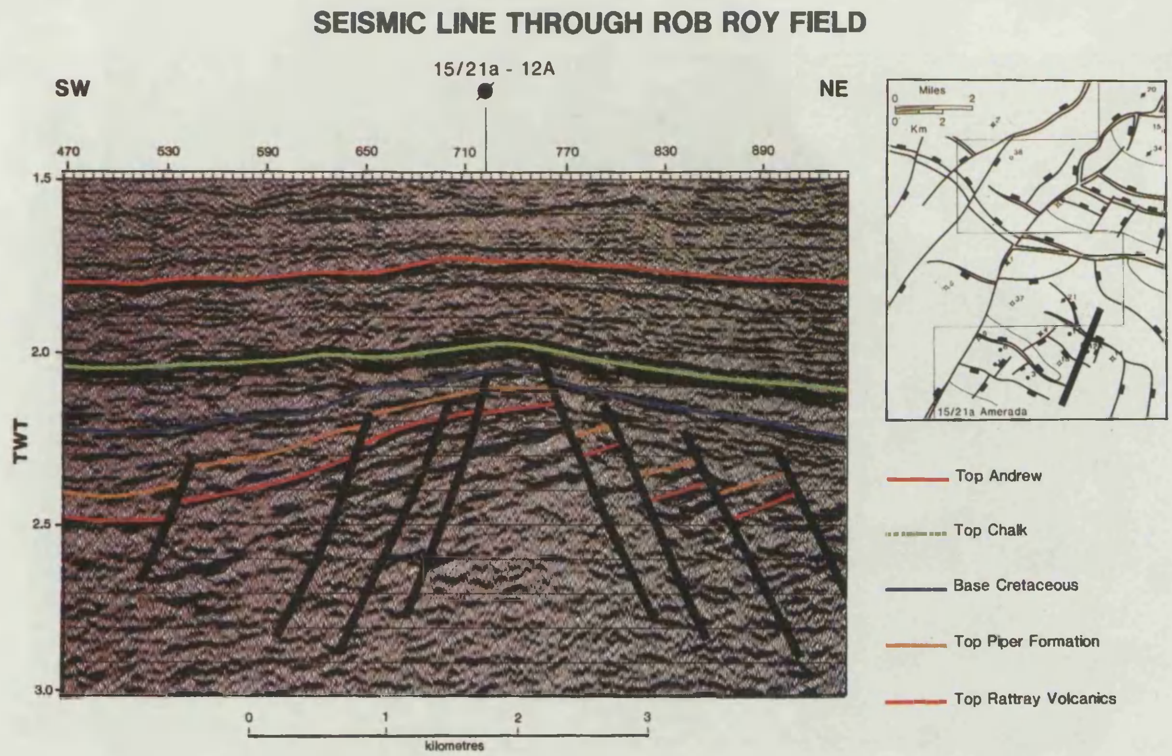

Fig. 11. Block 15/21: seismic line through the Rob Roy Field.

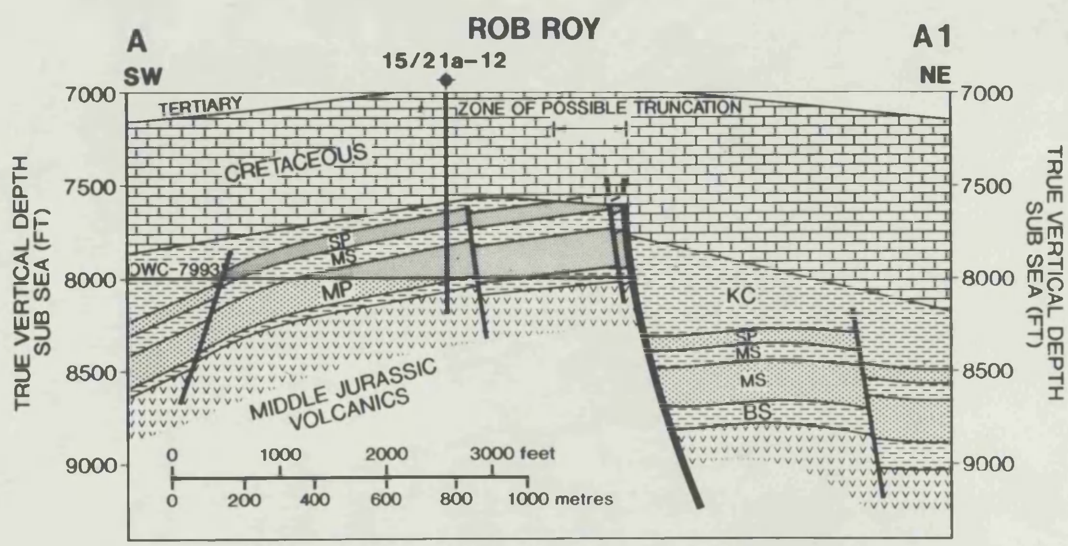

Fig. 12. Block 15/21: Structural cross section through the Rob Roy Field.

of the Rob Roy Field (Fig. 9). Here a maximum thickness of more than 500 ft of Piper–Sgiath has been proven by drilling, with thinning occurring both eastward towards Rob Roy and westward towards Ivanhoe, where the combined Sgiath and Piper interval is less than 300 ft thick.

The WNW–ESE Witch Ground trend faults also display strong control on the isochore pattern (Fig. 9). However, these faults are not considered to have been active during deposition of the Sgiath and Piper Formations, with the thinning seen along the crests of west–northwest trending fault blocks being a function of crestal erosion of rotating fault blocks, that occurred during the deposition of the Kimmeridge Clay. Several wells, such as 15/21–1 and 15/21–6 contain thick paralic and coal-bearing Sgiath sequences indicating that these areas were structurally low during the initial

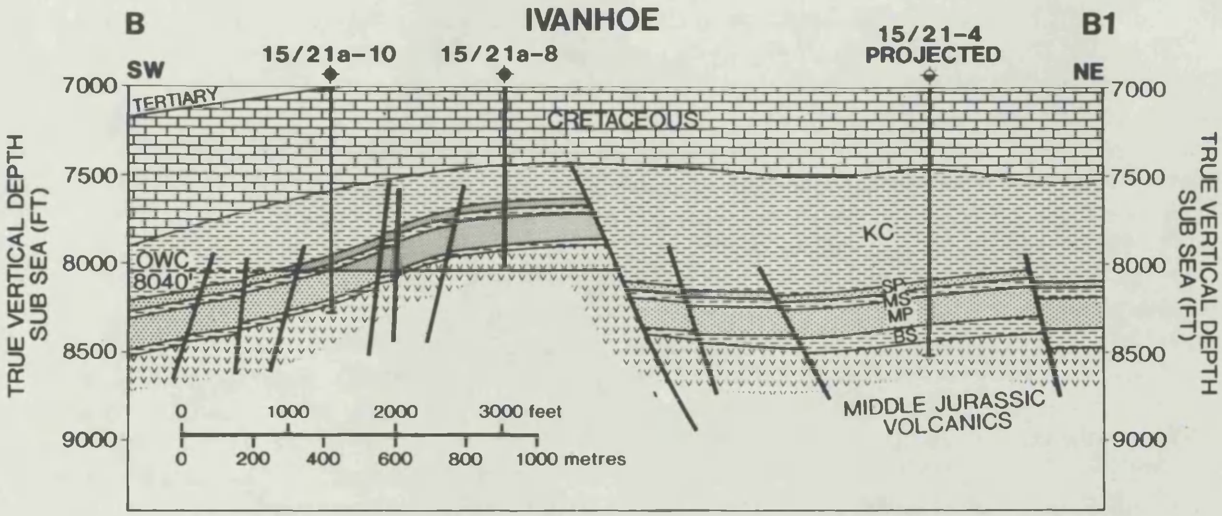

Fig. 13. Block 15/21: Structural cross section through the Ivanhoe Field.

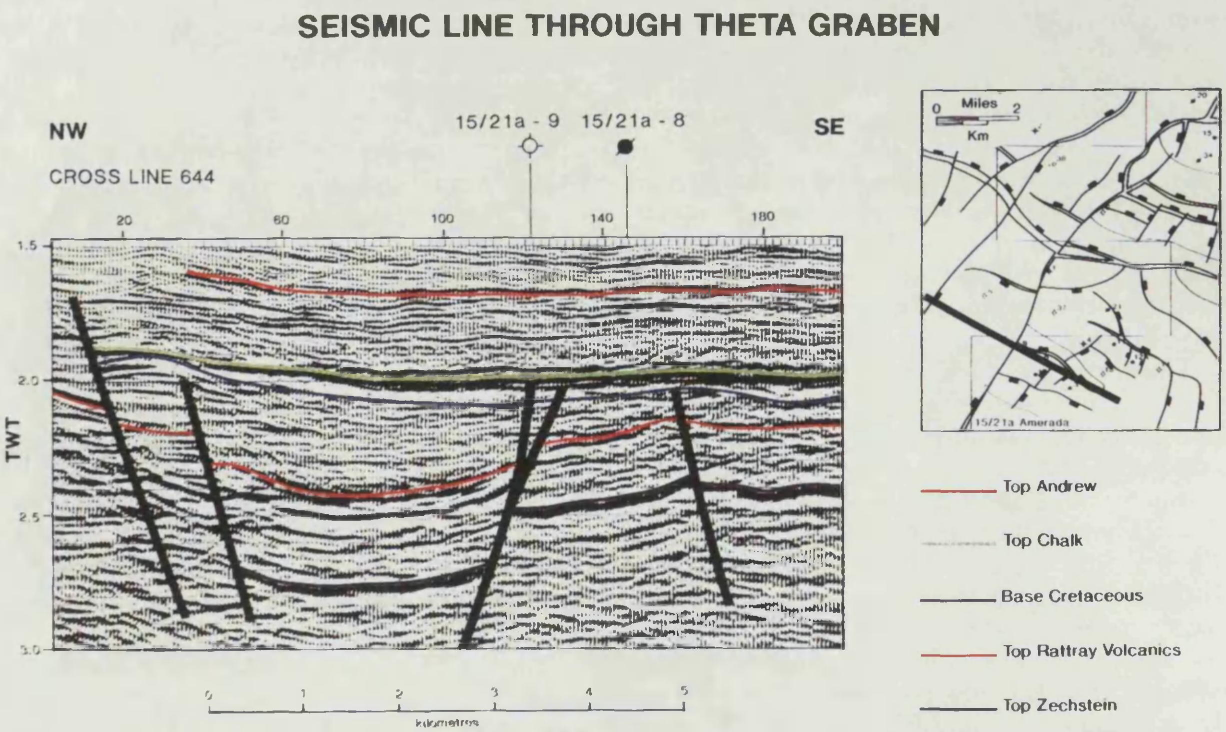

Fig. 14. Block 15/21: Seismic line illustrating the Theta Graben.

phase of Upper Jurassic sedimentation. These truncated sequences are unconformably overlain by Cretaceous Chalk and Kimmeridge Clay, respectively, in the 15/21–1 and 15/21–6 wells, testifying to the major phase of uplift and erosion which commenced in the late Jurassic and continued into Cretaceous times.

Tectonic controls on Kimmeridge Clay Formation deposition

The isochore map of the Kimmeridge Clay Formation in Block 15/21 (Fig. 10) displays marked contrast to the pattern illustrated for the Sgiath/Piper interval. The major depocentre lies within the axial part of the North Halibut Graben and is oriented in an east-west direction. This change in thickness pattern is related to the onset of significant movement on the west-northwest 'Witch Ground Trend' faults, connected with the opening of the Witch Ground Graben. The thickest sequence of the Kimmeridge Clay drilled to date on Block 15/21 occurs in the 15/21–2 well, where more than 3000 ft of section was found.

Within the North Halibut Graben a number of tilted fault blocks are developed, commonly backtilted to the southwest. Fault blocks of this type form the structural traps in the Scott Field in the eastern part of Block 15/21 (Fig. 10), where the Kimmeridge Clay Formation displays marked thinning over the crests of individual fault blocks.

The Halibut Horst and its eastward continuation, the Halibut Horst Spur, are interpreted to have formed during the deposition of the Kimmeridge Clay Formation. On the Halibut Horst itself and on much of the Halibut Horst Spur, there is no Kimmeridge Clay Formation preserved. Intense erosion of these areas during deposition of the Kimmeridge Clay led to the removal of the Piper Sands, which were redeposited as submarine fan-sands of the Claymore Member. These Claymore Sands have been found in wells both to the north (15/21−2) and to the south (15/21−5) of the Halibut Horst.

Over the Ivanhoe/Rob Roy Platform, relatively thin sequences of the Kimmeridge Clay Formation occur and range up to about 800 ft (Fig. 10). The Ivanhoe and Rob Roy Fields are tilted fault block traps defined by westnorthwest Witch Ground Trend normal faults. These fault blocks are also backtilted to the southwest and the Kimmeridge Clay thins over the crests, with less than 100 ft preserved on the crest of Rob Roy Field.

The northerly and northeasterly Viking Trend faults, dominant during deposition of the Sgiath and Piper Formations, continued to effect the depositional pattern of the Kimmeridge Clay Formation. In the 15/21−5 well, within the Theta Graben, more than 800 ft of Kimmeridge Clay is present and seismic evidence indicates further thickening to the southwest. It seems likely that pre-existing Viking Trend faults were exploited as transfer faults, between the major Witch Ground Trend fault blocks, during the Late Cimmerian phase of extension and block rotation.

Seismic and structural cross sections illustrating Jurassic tectonism

Seismic lines and structural cross sections through the Ivanhoe and Rob Roy area illustrate Jurassic tectonism. A northeast−southwest seismic line through the Rob Roy Field (Fig. 11) clearly displays the tilted fault block nature of the structure. The most prominent seismic events are at Top Chalk, Base Cretaceous and Top Middle Jurassic Volcanics. The Top Piper Event is mappable over parts of the field area, but is often masked by Base Cretaceous reflections in the crestal part of the structure. In a gross structural sense the Piper Formation is concordant with the underlying Middle Jurassic Volcanics event, and formed a 'pre-rift' sequence, that is overlain by the 'syn-rift' Kimmeridge Clay Formation.

The structural cross section through the 15/21a−12 Rob Roy well (Fig. 12) illustrates the marked thinning of the Kimmeridge Clay Formation over the crest of the structure. On the crest of the Rob Roy Field footwall, adjacent to the major bounding normal fault, erosion of the uppermost Piper Formation has been postulated from seismic interpretation and has recently been proved in development drilling. Usually a thin veneer of Kimmeridge Clay is present, but fault movement continued into the early Cretaceous and in places the Kimmeridge Clay may be entirely eroded. Thick sequences of Kimmeridge Clay Formation occur to the northeast of the Rob Roy Field, in the hanging wall block.

This variation in thickness of the Kimmeridge Clay Formation is not seen in the underlying Piper/Sgiath sequence. As is apparent on the structural cross section (Fig. 12) this interval thickens from southwest to northeast, toward the crest of the Rob Roy Field, indicating that the structure post-dates deposition of this sequence.

A northwest−southeast structural section through the Ivanhoe Field, intersecting the 15/21a−8 and 10 wells (Fig. 13) also illustrates thinning of the Kimmeridge Clay Formation onto the crest of the structure, but activity on the major bounding fault appears to have died out during the Jurassic, as there is no displacement seen at Base Cretaceous.

The northeasterly 'Viking' trend faults that define the Theta Graben are illustrated on the seismic line shown in Fig. 14. This line is oriented WNW−ESE, parallel to the major Witch Ground trending faults. In the eastern part of the line the Ivanhoe Field is evident as a major high fault block covered by a relatively thin Jurassic sequence. The major down to the west fault that forms the eastern boundary to the Theta Graben is visible on Fig. 14 to the west of the 15/21a−9 well. Across this fault there is marked thickening of the Upper Jurassic, as defined by the interval between the Base Cretaceous and the Top Middle Jurassic Volcanics. However, there is also marked thickening in the deeper section, between the Top Middle Jurassic and the Top Zechstein, indicating earlier, pre-Upper Jurassic movement on this fault. This is highlighted by the thickening of the Middle Jurassic Volcanics package, identified by high-amplitude reflectors, across the fault. These Viking trend faults were therefore certainly active in Mid-Jurassic times, but are likely to have been initiated earlier in the Mesozoic, probably during the Triassic.

A structural cross section across the Theta Graben (Fig. 15) parallel to the seismic line (Fig. 14), illustrates the rapid thickening of the Piper/Sgiath interval across the fault to the west of 15/21a–9. The thick sequence of Piper/Sgiath Formations proved by the 15/21–5 well, is restricted to the Theta Graben, with much reduced thicknesses penetrated in Ivanhoe Field wells to the east.

Jurassic tectonism: conclusions

From the foregoing examination of seismic and isochore data at both regional (Outer Moray Firth) and local (15/21) scale, a number of conclusions can be drawn concerning Jurassic tectonism and its effect upon sedimentation and structure.

(i) North–south and northeast–southwest 'Viking' Trend Faults were active in Mid-Jurassic times and form the principal control upon the isochore patterns of the Fladen Group and the Sgiath and Piper Formations.

(ii) If the assumption is made that the extension direction is orthogonal to the major normal faults, this would argue for an early phase of east–west extension in the Outer Moray Firth, which formed a north–south basin, parallel to the Viking Graben.

(iii) There is no evidence that the west-northwest Witch Ground Trend faults were active during the deposition of the Fladen Group, or the Sgiath or Piper Formations. Some faults of this orientation may have existed as transfer faults, but the major structural feature of the Witch Ground Graben, had not been formed. Therefore during this Mid Cimmerian phase of Jurassic tectonism the North Sea rift system did not display the triple-junction geometry as defined by the Viking, Witch Ground and Central Graben intersections.

(iv) A major change in tectonic regime occurred during the Kimmeridgian, with the onset of opening of the Witch Ground Graben along WNW–ESE 'Witch Ground' Trend faults. This Late Cimmerian phase of rifting was much more intense than the earlier tectonism.

(v) Once again, if the assumption is made that the extension direction is orthogonal to the major normal faults, this argues for a northeast–southwest orientated extensional regime, suggesting a change in extension direction during the later Jurassic.

(vi) The tilted fault block structural traps of the Outer Moray Firth are defined by Witch Ground Trending faults and were formed during Kimmeridgian to early Cretaceous times. The Ivanhoe, Rob Roy, Scott and Piper Fields are all tilted fault block traps of this type.

(vii) The Witch Ground Graben is a symmetrical feature with fault blocks backtilted both to the northeast, in the north, as shown by the Piper Field (Fig. 16) and to the southwest, in the south, as shown by the Ivanhoe, Rob Roy and Scott Fields.

(viii) The Witch Ground Trend faults are important in controlling the distribution of Claymore Sands, which accumulated as toe of slope submarine fans (Gustav & Boote 1987). These Witch Ground faults also effect the isochore pattern of the Sgiath and Piper Formations through widespread erosion of the crestal parts of tilted fault blocks, as seen in the Rob Roy Field.

(ix) Many of these conclusions are supported by Maher (1980) in his work upon the Piper Field (Fig. 16). Maher (1980) stated that only a few faults could be shown to have been active during deposition of the Piper Formation, the principal one of these being the 'D' fault which is orientated in a northeasterly direction. Furthermore, he demonstrated that erosion occurs along the crestal part of the footwall associated with the northwest trending faults.

Timing of Jurassic events

Dating the Jurassic sequences of the Outer Moray Firth has relied upon radiometric techniques for the Middle Jurassic Rattray Volcanics, and micropalaeontological zonation for the Upper Jurassic sequence (Harker *et al.* 1987; O'Driscoll *et al.* this Volume). Of particular importance has been the use of dinoflagellate cysts and several zonation schemes have been proposed utilising these palynomorphs. Wollam & Riding (1983) proposed 18 dinoflagellate cyst assemblage zones covering the interval from latest Triassic to earliest Cretaceous. The latest Oxfordian to earliest Port-

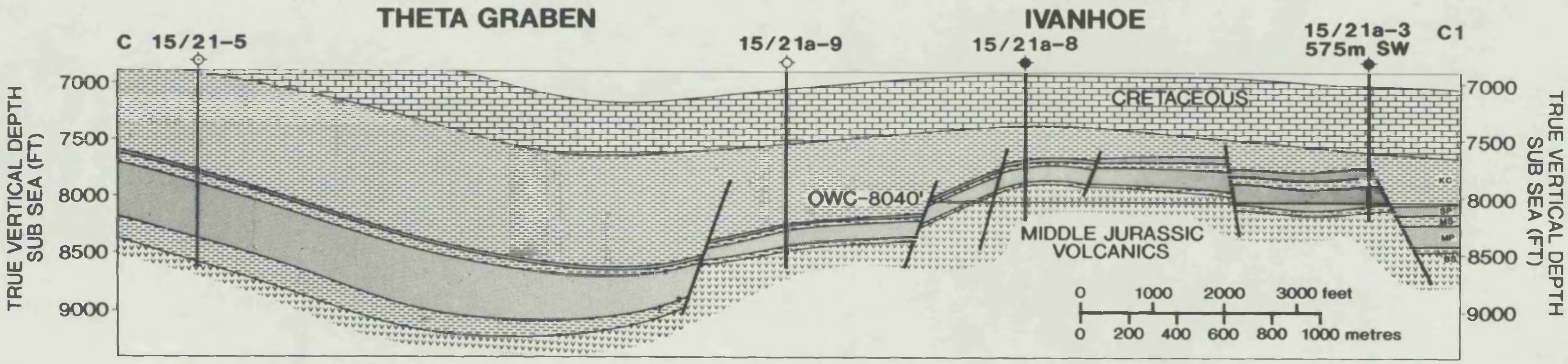

Fig. 15. Block 15/21: Structural cross section through the Theta Graben.

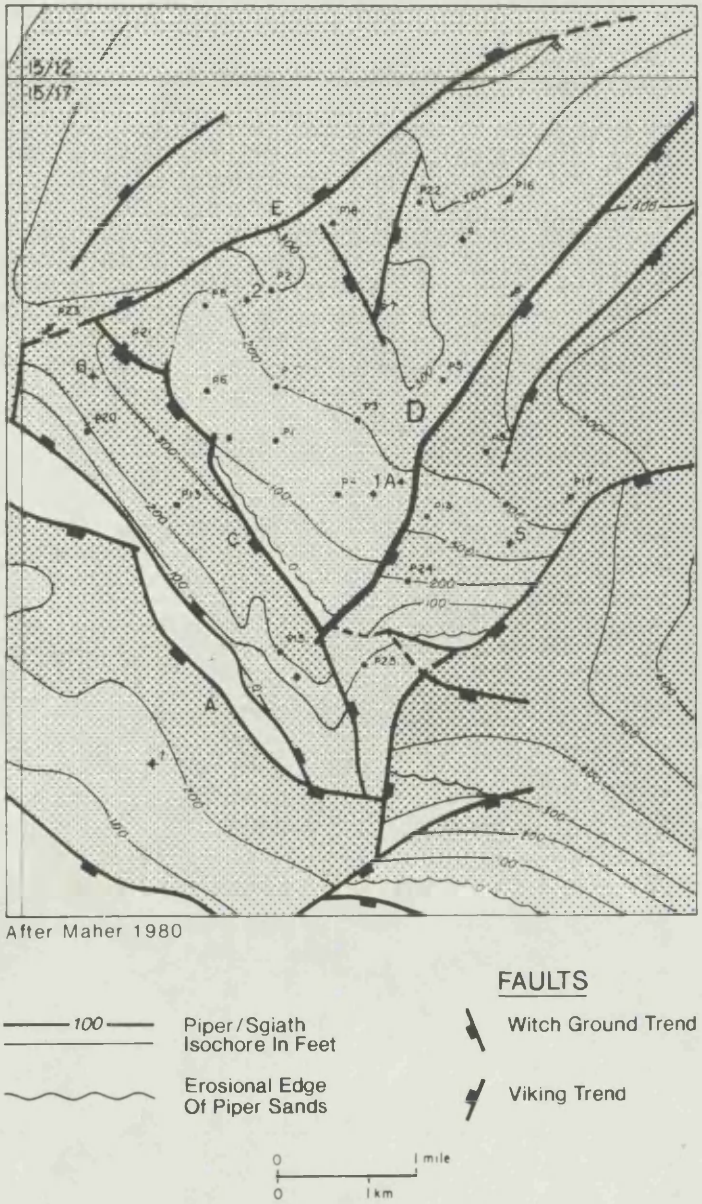

Fig. 16. Block 15/17: isopach map of the Piper and Sgiath Formations highlighting fault trends (after Maher 1980).

landian part of this zonation scheme has been revised by Riding & Thomas (1988).

Within Block 15/21 cores from several wells have yielded well preserved ammonites. Identification of these ammonites has allowed more precise definition of the timing of transgressive and tectonic events. Ammonites have most commonly been recovered from the Mid-Shale Unit of the Piper Formation, but occasional specimens have also been recovered from the lowermost part of the Kimmeridge Clay Formation. This distribution certainly displays sample bias, as far more core material has been obtained from the Mid-Shale Unit than from any of the other Upper Jurassic shale sequences. To date, no identifiable ammonites have been recovered from the Marine Shale Unit of the Piper Formation.

Ammonites identified from four wells in the Rob Roy Field are shown in Fig. 17. Identification of these ammonites has shown that the Mid-Shale Unit represents the lowermost part of the Kimmeridgian, with definitive *baylei*, *cymodoce* and *mutabilis* forms and assemblages recovered. The dating of the lowermost part of the Mid Shale Unit as *baylei* Zone, the lowermost zone within the Kimmeridgian, suggests strongly that Main Piper Sand deposition was terminated by the base Kimmeridgian transgression (Rawson & Riley 1982) and that the

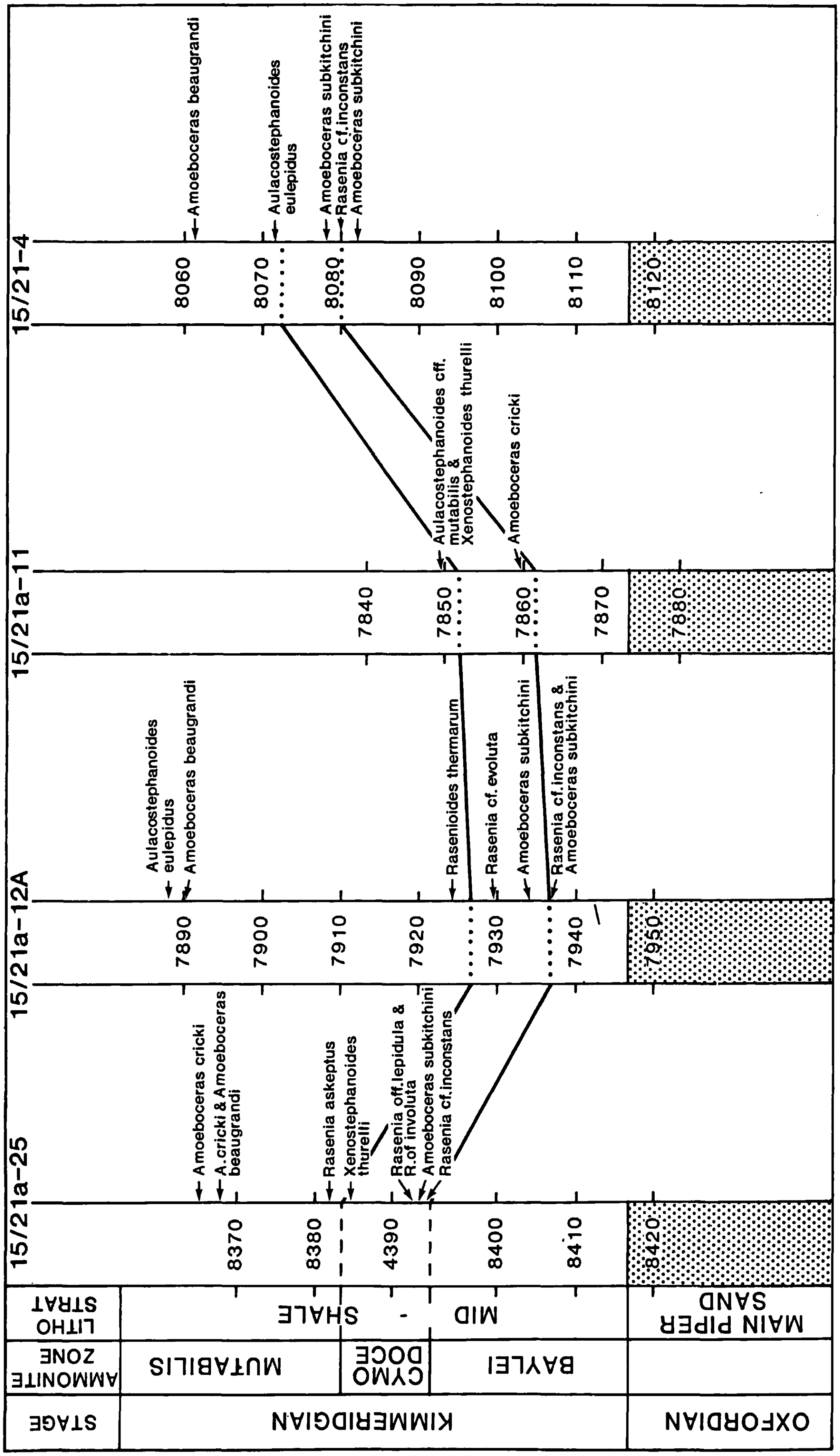

Fig. 17. Block 15/21: Rob Roy Field Ammonite Zonation.

junction between the Mid Shale and the Main Piper must be very close to the Oxfordian/ Kimmeridgian boundary (Fig. 18).

A zonal subdivision of the Lower Kimmeridgian stage *sensu anglico* was proposed first by Salfeld (1914), who created five ammonite zones: *baylei* (lowest); *cymodoce*; *mutabilis*; *yo* and *pseudomutabilis* (highest). Ziegler (1962) replaced the two highest with the *eudoxus* and *autissiodorensis* Zones. More precise definition of zonal boundaries is still needed and, as yet, no formal subzonal scheme has been applied to Northwest Europe. However, it appears from a number of richly fossiliferous sequences that three faunas can be recognised for the *cymodoce* Zone and three for the *mutabilis* Zone, allowing identification of lower, middle and upper parts of these zones (Fig. 19, Birkelund *et al.* 1978, 1983).

The ammonite fauna recovered from Rob Roy wells indicates that Mid Shale deposition continued at least until mid-*mutabilis* Zone times, with the Supra Piper Sand being of upper *mutabilis* Zone age (Fig. 18).

Ammonites recovered from the basal part of the Kimmeridge Clay Formation in the 15/21a–25 well indicate an earliest *eudoxus* Zone age, from the co-existence of *Amoeboceras kochi* and *Aulacostephanites eulepidus*. The final transgressive pulse that terminated Piper Sand deposition and heralded the onset of Kimmeridge Clay deposition, can therefore be dated as earliest *eudoxus* Zone (Fig. 18), as suggested by Harker *et al.* (1987).

Concomitant with the study of the ammonite fauna, samples have been prepared for palynological analysis and from these more than 50

NW EUROPEAN AMMONITE ZONES	FAUNAL SUBDIVISIONS
Aulacostephanus autissiodorensis	
Aulacostephanus eudoxus	
Aulacostephanoides mutabilis	Aspidoceras orthocera
	Aulacostephanoides mutabilis
	Rasenioides askepta
Rasenia cymodoce	Rasenia evoluta
	Rasenia involuta
	Rasenia cymodoce
Pictonia baylei	Rasenia inconstans

Fig. 19. Lower Kimmeridgian Ammonite Zones and informal subdivisions.

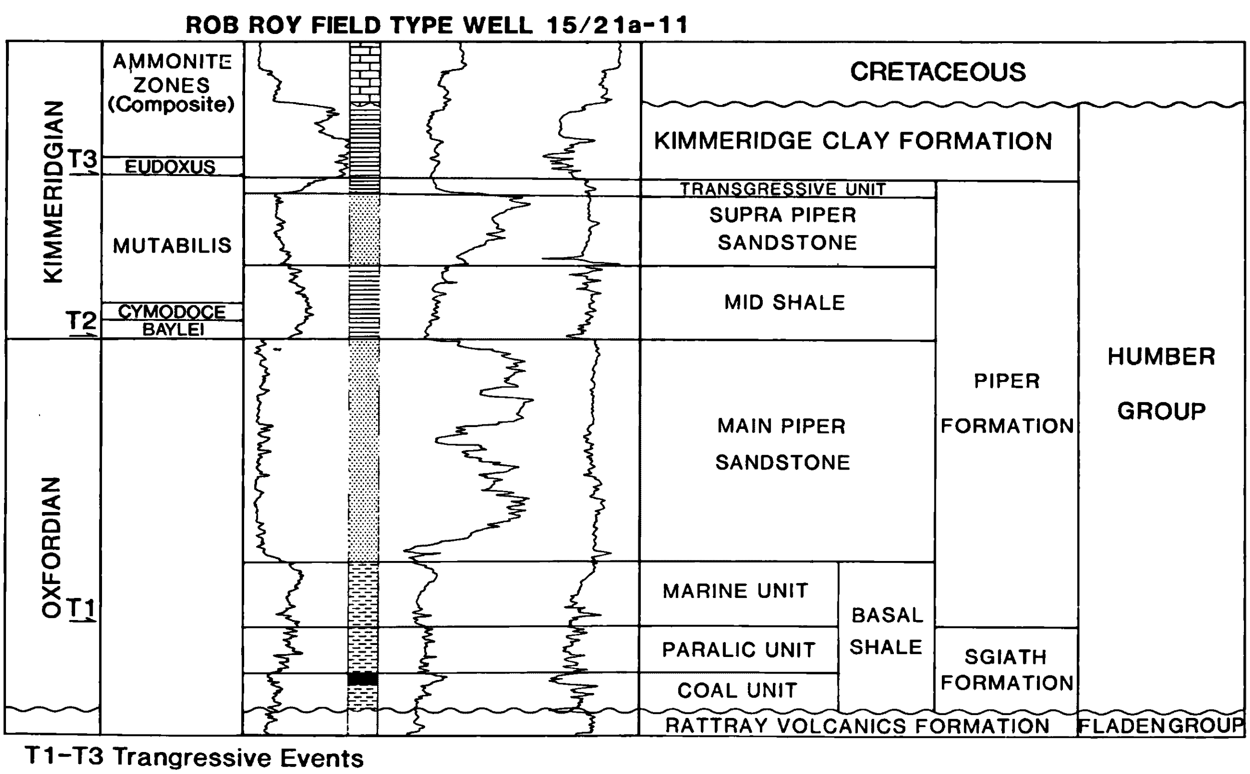

Fig. 18. Block 15/21: Jurassic Ammonite Biostratigraphy.

STAGE	RIDING & THOMAS 1988 AMMONITE ZONE	ZONE	SUB-ZONES	RANGE-TOPS	RANGE-BASES	BLOCK 15/21a AMMONITE ZONE
LOWER KIMMERIDGIAN	AUTISSIO-DORENSIS	ENDOSCRINIUM LURIDUM (E l)	c	← E. luridum		
	EUDOXUS		c			EUDOXUS
	MUTABILIS		b	← S. scarburghense A.dictyotapyra		MUTABILIS
	CYMODOCE		a	← T.dangeardi E.galeritum	← S?inaffecta S?paeminosum P.pannosum	MUTABILIS
	BAYLEI	SCRINIODINIUM CRYSTALLINUM (Sc)	d	← S.crystallinum S.orbis N.pellucida	← C.longicorne O.patulum	CYMODOCE / BAYLEI
UPPER OXFORDIAN	ROSENKRANTZ1		c	← C.ornatum		
	REGULARE		b		← O.balia D.tuberosum	

Fig. 20. Comparison of Block 15/21 Ammonite and Dinocyst Zonation with Riding & Thomas (1988).

taxa of dinoflagellate cysts have been identified, including many of the critical taxa used in zonation by Riding & Thomas (1988). However, as can be seen in Fig. 20, the correlation of the dinocyst zones to the Boreal ammonite zonal sequence in Block 15/21 does not agree in detail with the scheme published by Riding & Thomas (1988) for the Dorset coastal sections. This anomaly is explained by the extended ranges in the 15/21 wells of *Scriniodinium crystallinum* and *Endoscrinium galeritum*, both these forms occurring in conjunction with *mutabilis* Zone ammonites (Fig. 20). Other key taxa utilized by Riding & Thomas (1988) are absent in the 15/21 sequences and these include *T. dangeardi, S. inaffectun, D. tuberosum* and *C. ornatum*. Work is continuing to clarify the anomaly between the ammonite and dinocyst biostratigraphy.

In conclusion, the identification of ammonites has allowed precise ages to be assigned to two of the three major transgressive events seen in the Upper Jurassic in Block 15/21. No ammonites have been recovered from the first transgressive event represented by the Marine Unit of the Piper Formation, but the Mid-Shale transgression has been demonstrated to be basal Kimmeridgian in age and the Kimmeridge Clay transgression has been dated as early *eudoxus* Zone. It seems most likely that the Kimmeridge Clay transgression accompanied the onset of Late Cimmerian tectonism within Block 15/21, suggesting a *eudoxus* Zone age for this tectonic event. In contrast, no tectonic control is apparent accompanying the Mid-Shale transgression, although such a relationship may become apparent with further evaluation.

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