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Microfaunal investigation of the Early Toarcian (Lower Jurassic) extinction event in N.W. Europe

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MICROFAUNAL INVESTIGATION OF THE EARLY TOARCIAN (LOWER JURASSIC) EXTINCTION EVENT IN N. W. EUROPE

by

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Abstract

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Microfaunal investigation of the Early Toarcian (Lower Jurassic) extinction event in North-West. Europe

The Early Jurassic was a time of rapidly rising sea-level associated with the extensive spread of anoxic bottom waters. Sea-level rise across the Pliensbachian - Toarcian boundary culminated in the *falciferum* Zone of the Toarcian and is one of the best authenticated eustatic events in the Jurassic. This major transgressive pulse was marked by deep water marine sequences and was associated with the deposition of organic-rich shales.

The development of anoxia coincides with a notable period of mass extinction of the marine fauna. High resolution sampling and study of the microfaunas through sequences in N. W. Europe confirm that benthic foraminiferal faunas were similarly affected by an early Toarcian *falciferum* Zone event. Samples were analysed from Pliensbachian - Toarcian mudstone, clay and shale sequences of the south Dorset Coast, the Midlands, the Yorkshire Coast, southern France and southwest Germany. The sections studied show distinct changes in assemblages across the Pliensbachian - Toarcian boundary and in the basal zones of the Toarcian.

Evidence for a foraminiferal extinction event in the Pliensbachian - Toarcian includes the elimination of the important Lower Jurassic *Lingulina tenera, Frondicularia terquemi* and *Marginulina prima* plexus groups, initiating a significant period of turnover of the microfauna. The foraminiferal extinction event recorded in the Lower Toarcian sections of north west Europe is only significant at species level. No extinctions at the family-level occurred.

A marked change also occurred in the character of associated nodosariid assemblages: the uniserial forms of *Nodosaria, Frondicularia* and *Lingulina*, dominating the Pliensbachian assemblages, were largely replaced by coiled *Lenticulina* in the early Toarcian. A reduction in test size and a decline in species diversity, compared with Hettangian to Sinemurian foraminiferal assemblages, reflect the development of low oxygen conditions followed by a subsequent renewal of the microfauna in the Middle Toarcian. The foraminiferal data show no evidence of progressive displacement of older by younger faunas. Instead certain species only expanded their populations and diversity significantly after the extinction of similar niche-occupying species.

The Pliensbachian - Toarcian (Lower Jurassic) sediments of the north Yorkshire coast contain highly organic-rich shales where the sequence stratigraphic significance is somewhat obscure. Benthic foraminiferal species distribution (as a function of organic flux and oxygenation) allowed palaeobathymetry to be determined on quantitative assemblage characteristics.

In parallel with this methodology, a suite of trace elements (including Mn, Ca, Fe, and Al) have been analysed following nitric and hydrofluoric acid digestion. Maxima of Ca and Mn occur at the base of the *falciferum* Subzone (*falciferum* Zone). It is suggested that these maxima are an artefact of condensation of carbonate fossiliferous material due to sediment starvation and correspond to published estimates of a maximum flooding surface. Interpretations of the benthic foraminiferal assemblages surrounding this event provide further support for a transgressive event associated with the development of low oxygen conditions and the deposition of organic-rich shales.

Additional Lower Jurassic, Hettangian to lower Pliensbachian, sequences were investigated for the purposes of establishing their foraminiferal correlation potential as candidate Global Stratotype Sections and Points for the basal Sinemurian and basal Pliensbachian.

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Author's declaration

At no other time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

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Publications and posters:

HYLTON, M. D. 1998. A preliminary analysis of the foraminifera from the Hettangian - Sinemurian boundary of East Quantoxhead, West Somerset, *Geoscience in south-west England*, 9, 203-208.

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Presentations and Conferences Attended:

"Recoveries '97", UNESCO-IGCP Project #335 "Biotic Recoveries from Mass Extinctions" Final Conference Prague, Czech Republic, Sept 1997.

5th International Symposium on the Jurassic System, Vancouver, August 12-25, 1998.

Palaeontological Association Annual Meetings: Birmingham, 1996; Cardiff, 1997; Portsmouth, 1998; Manchester, 1999.

Ussher Society Annual Conferences: Bideford, 1997; Penzance, 1998.

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Signed ....

Date 8/3/00

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Chapter 1 Introduction

1.1 Historical background

> *No one I think can have marvelled more at the extinction of species, than I have done...species and groups of species gradually disappear, one after another, first from one spot, then from another, and finally from the world.*
>
> *(Charles Darwin, 1859, Origin of Species)*

The phenomenon of mass extinction has recently become one of the most studied topics in palaeontology. The main factors for this are the controversial hypotheses that, first, the Cretaceous - Tertiary transition events were caused by the impact of a huge bolide (Alvarez *et al.* 1980); second, that mass extinctions are periodic (Raup and Sepkoski, 1984, 1986) possibly caused by comet showers triggered by an unseen solar companion (Davis *et al.*, 1984; Whitmire and Jackson, 1984); and third, that the biotic effects of mass extinctions are qualitatively different from all other phenomena seen in the fossil record (Jablonski, 1986; Hart, 1996). These hypotheses have become the subject of intense debates and have stimulated much new and productive empirical and theoretical research. The compilation and use of large taxonomic databases (e.g., Sepkoski, 1982, 1992; Benton, 1993) and the controversy over the mechanisms of widely studied extinction events such as the Cretaceous - Tertiary boundary, resulted in a whole new area of research concerning the processes of, and evidence for, mass extinction. Indeed the definition and scope of the term 'mass extinction' is still the subject of much debate and it must be remembered that while *extinction* is a continual process, the differences between mass extinctions and the continually occurring background extinctions are, in most cases, considerable (Donovan, 1989). Donovan (1989) also makes a case against regarding extinction as comprising these two end-members and a further distinction between mass, regional and taxon level extinctions (Table 1).

	Background	*Mass*	*Regional*	*Taxon*
Occurrence	Continuous	Episodic	Episodic	Episodic
Rate	Gradual	Fast	Fast	Fast
Effect	Local	Global	Broad area	Global
Species affected	Few	Numerous	Many	Single Taxon

Table 1. A comparison of the essential features of mass, background, regional and taxon extinctions. (after Donovan, 1989).

In recent years there has been a rapid growth of research on the patterns, rates, causes and consequences of extinction (Walliser, 1986; Sharpton and Ward, 1990; Hart, 1996). The fossil record of evolution is now better known, new stratigraphic sections have been examined in detail and additional markers of environmental change have been discovered in the rock record (Jenkyns and Clayton, 1997; Parisi *et al.*, 1996). Prior to these works, the modern study of mass extinctions began with a series of papers in the 1950s and 1960s principally focused on the end-Permian event (Schindwolf, 1954; Beurlen, 1962; Newell, 1962). This culminated with Newell's (1967) overview of Phanerozoic extinctions pertinently entitled 'Revolutions in the history of life'. Besides the major extinctions at the end of the Palaeozoic and Mesozoic eras, Newell recognised four other events in the Phanerozoic record of marine families which were also dramatically sudden in the context of the much longer time intervals preceding and following them. These six events took place at the end of the Cambrian, Ordovician, Permian, Triassic, Cretaceous and near the end of the Devonian. Raup and Sepkoski's (1982) much later statistical analysis of extinction rate, expressed as families going extinct per stratigraphic stage, confirmed the last five as major episodes of mass extinction (Figure 1a) and these have generally been

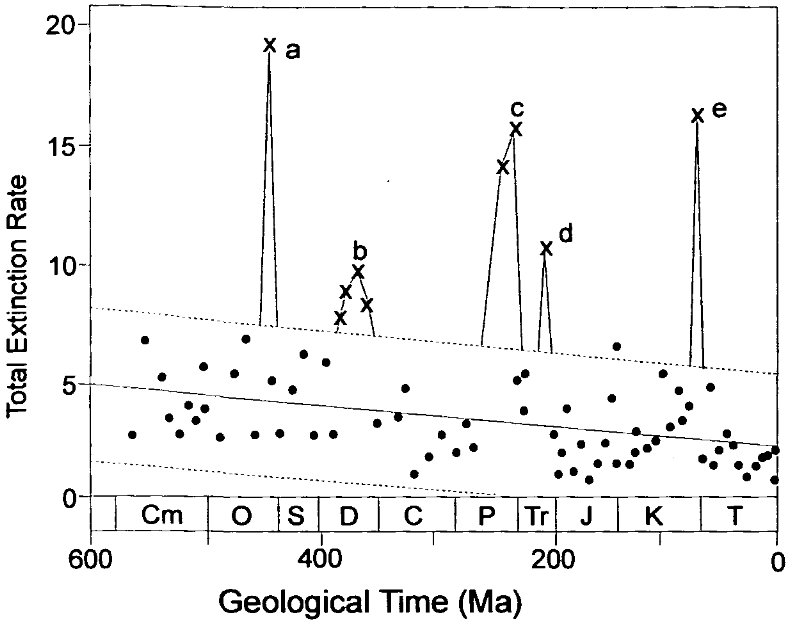


Figure 1a. Extinction rates (families/m.y.) of marine animals during the Phanerozoic showing the 'big five' mass extinctions as clear peaks with crosses standing above the enveloped background extinction level: (a) Late Ordovician; (b) Late Devonian; (c) Late Permian; (d) Late Triassic; (e) Late Cretaceous. Cm represents Cambrian; O, Ordovician; S, Silurian; C, Carboniferous; P, Permian; Tr, Triassic; K, Cretaceous; T, Tertiary. Data after Hallam & Wignall (1997).

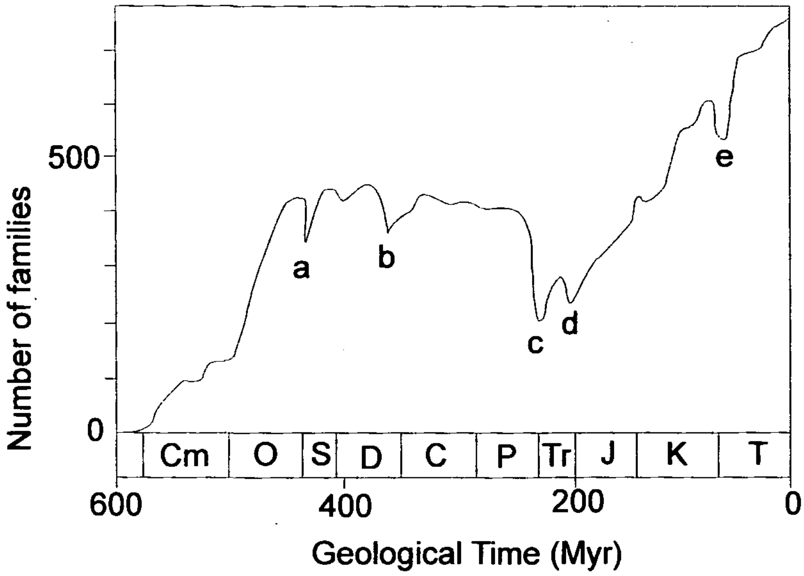


Figure 1b. Marine family diversity during the Phanerozoic showing the long-term increase punctuated by diversity crashes caused by the 'big five' mass extinction events. Diversity decreases correspond to the following percentage losses of families: (a) 12%; (b) 14%; c) 52%; (d) 12%; (e) 11%. Abbreviations as in Fig 1a. Data after Hallam & Wignall (1997).

accepted since as the 'big five'; they also show up as abrupt decreases in diversity (Figure 1b).

The fossil record of marine invertebrates generally has the advantage of abundant specimens, good stratigraphic control, closely spaced samples, uniform preservation quality and broad geographic distribution. The quality, however, varies substantially from group to group and for some, notably the echinoderms, the fossil record is rather poor (Benton and Simms, 1995). Nonetheless, research in recent years, involving many additions, corrections and reinterpretations of both taxonomy and stratigraphy, has only served to refine the five major events (Sepkoski, 1993; Benton and Storrs, 1994; Jablonski, 1994; Benton, 1995). Sepkoski's (1986) family - and genus - level compendia have allowed the species-level extinction intensities of the five major mass extinctions to be calculated (Table 2).

	Families		Genera	
Mass Extinction	Observed Extinction (%)	Calculated species loss (%)	Observed Extinction (%)	Calculated species loss(%)
End-Ordovician	26	84	60	85
Late Devonian	22	79	57	83
End-Permian	51	95	82	95
End-Triassic	22	79	53	80
End-Cretaceous	16	70	47	76

Table 2. Extinction intensities at the five major mass extinctions in the fossil record: species level estimates based on a rarefaction technique. From Hallam & Wignall (1997).

On the basis of his compendium of marine genera, Sepkoski (1986) recognised no fewer than 27 Phanerozoic extinction events, which can be called major and minor mass extinctions. Hoffman (1989) contends, however, that many phenomena that have traditionally been called 'mass extinctions' are in fact clusters of extinction events roughly associated in geological time. Hoffman (1989) also added the caveat that not all recognised mass extinctions comprise several independent, but accidentally aggregated, events. For example, Hoffman (1989) quotes the end-Permian extinctions, among marine animals that could be fossilised, as undoubtedly the most severe in the Phanerozoic and while the geological record of the Permo-Triassic transition was limited by a marine regression and consequent erosion, the record contained strong evidence for a change in the world ocean-atmosphere system. Accordingly, the end-Permian biotic change fully deserved to be called a 'mass extinction' because the record seemed to indicate a single process that must have caused a true mass extinction. However, recent detailed studies of P-Tr boundary sections in South China, Greenland, Japan and Italy have greatly increased the knowledge of the event and subsequent studies have revealed two extinction events, separated by an interval of radiation (Hallam & Wignall, 1997). The full extinction scenario is now thought to have resulted from combined global warming and marine anoxia in a complex chain of events (Wignall and Twitchett, 1996; Hallam and Wignall, 1997).

A further issue in global-scale studies of extinction events is that family-level data has been accepted as a compromise between biological meaningfulness and palaeontological reliability (e.g., Benton, 1995). The use of species as a natural genetic unit would be preferred in such studies because the amount of difference between species in a family may differ considerably from one taxonomic group to another. While species are commonly used in the quantitative analysis of local-scale extinction patterns, species-level data are hampered by the gaps in the fossil record that can make such data biased and unreliable (Signor and Lipps, 1982; Holland, 1995). Not withstanding the problems discussed, inherent in such studies, Jablonski (1986) points out that mass extinction events may be one of the most important factors in evolution - reducing diversity significantly and opening ecospace for the rapid evolution of new forms. Episodes of re-population, therefore, may record some of the most rapid, large-scale biotic changes in life history and are consequently worthy of detailed study.

1.1.1 Background: analysis and terminology

> *A mass extinction is any substantial increase in the amount of extinction (i.e., lineage termination) suffered by more than one geographically widespread higher taxon during a relatively short interval of geologic time, resulting in an at least temporary decline in their standing diversity (Sepkoski, 1986, p. 278).*

The Phanerozoic record of marine invertebrates is punctuated by numerous, geologically short-term intervals (generally < 3Ma) during which biotic diversity and abundance declined significantly (40% at the familial level and <63% at the generic level; Raup & Sepkoski, 1986). These intervals are termed *mass extinctions* and have been recognised by palaeontologists for over a century. The study of these events in the fossil record has consequently revealed many recurrent phenomena common to all biotic crises including mechanisms of survival, re-population and the hypothesis that extinction events occurred at regularly spaced intervals.

1.1.1.1 Periodicity of mass extinctions

The possibility that regularly spaced extinction events have punctuated the Earth's history was raised by Georges Cuvier in the early days of palaeontology, but the real debate on periodicity did not begin until a century and a half later when Fischer and Arthur (1977) proposed that a 32 m.y. cyclicity occurred in post-Palaeozoic extinctions. Based on a small data set, by the later standards of Sepkoski, they claimed to see periodic decreases in the diversity of ammonoid genera and globigerinid species associated with a changeover in the dominant top-predators in the oceans. Despite the similarity to later claims by Raup and Sepkoski, discussed below, Fischer and Arthur's contribution can not be considered to mark the start of the current periodicity debate. Many of their extinction events have not been subsequently confirmed (for example, the Bathonian and Valanginian events) while their two Tertiary extinctions, in the Oligocene and Pliocene, do not even appear to be shown in their own data (Fischer and Arthur, 1977, fig. 1). They do, however, deserve credit for being the first to recognise the end-Cenomanian mass extinction.

Raup and Sepkoski (1984, 1986) conducted a series of statistical analyses of the rate and intensity of extinction of marine invertebrate families and genera during the Phanerozoic. They concluded that the observed pattern of temporal distribution is best explained by assuming a significant contribution from an approximately 26 m.y. periodic signal in the later Phanerozoic, and perhaps a longer period signal in the Palaeozoic. This conclusion and Hoffman's (1985) suggestion that this empirical pattern of extinction peaks may in fact reflect nothing more than a random variation in extinction intensity through time triggered a heated debate. The proposal that mass-extinction events have occurred periodically, with a regular spacing of 26 m.y. (Raup and Sepkoski, 1984, 1986; Sepkoski and Raup, 1986; Sepkoski, 1989, 1990) is based on statistical analyses of family-level and genus-level compilations of global data on marine invertebrates. Out of a proposed 12 extinction peaks, 10 have been identified for the past 250 m.y. (Raup and Sepkoski, 1986; Sepkoski, 1990). However, many workers have re-examined Raup and Sepkoski's data and statistical methods in order to disprove this theory. Kitchell and Peña (1984) demonstrated that, if the magnitude of extinction peaks is taken into account alongside their spacing in time, a stochastic autocorrelation model fits the empirical pattern even better than does the periodic one. Kitchell and Estabrook (1986) show that approximately 8% of symmetrical random walks of the same length as the time series studied by Raup and Sepkoski produce patterns with their peaks spaced even more like 26 m.y. periodicity than in the empirical pattern. Ross (1987) shows that up to 35% of such random walks are statistically indistinguishable from the empirical pattern. Noma and Glass (1987) demonstrate that the historical pattern of marine animal extinctions has no more periodicity than expected to occur in more than 5% of the series of numbers produced by a 32-number roulette. Quinn (1987) re-analysed Raup and Sepkoski's data and failed to discover a significant periodicity of extinction. Hoffman (1989) holds the view that the hypothesis of extinction periodicity is not, therefore, unambiguously supported by the data and that its rival hypothesis of random distribution of mass extinctions in time is perfectly viable. With this growth of interest, the need has increasingly become apparent for more detailed analyses of all major and minor extinction events in order to resolve these arguments. Most recently, Benton's (1995) Family and Stage level analysis of the fossil record of microbes, algae, fungi, protists, plants and animals, finds no support for the periodicity of mass extinctions with seven peaks in the last 250 million years being spaced 20 to 60 million years apart.

1.1.1.2 Terminology

Mass extinction intervals are characterised by three dynamic processes: extinction, survival and recovery (Harries *et al.*, 1996). The typical sequence of events in a mass extinction is initiated by an extinction phase during which diversity falls rapidly, followed by a survival or lag phase of minimal diversity and then a recovery phase of rapid diversity increase. In practice, the distinction between the extinction phase and the survival phase is rather an arbitrary one as extinctions can continue into the survival phase. Within these phases several types of taxa are distinguished by their characteristics recorded from the fossil record. Figure 2 illustrates a general model compiled by Hallam & Wignall (1997) showing the phases and the range of responses of species during and after a mass extinction event. While the origins of most responses are self-evident, some require further clarification:

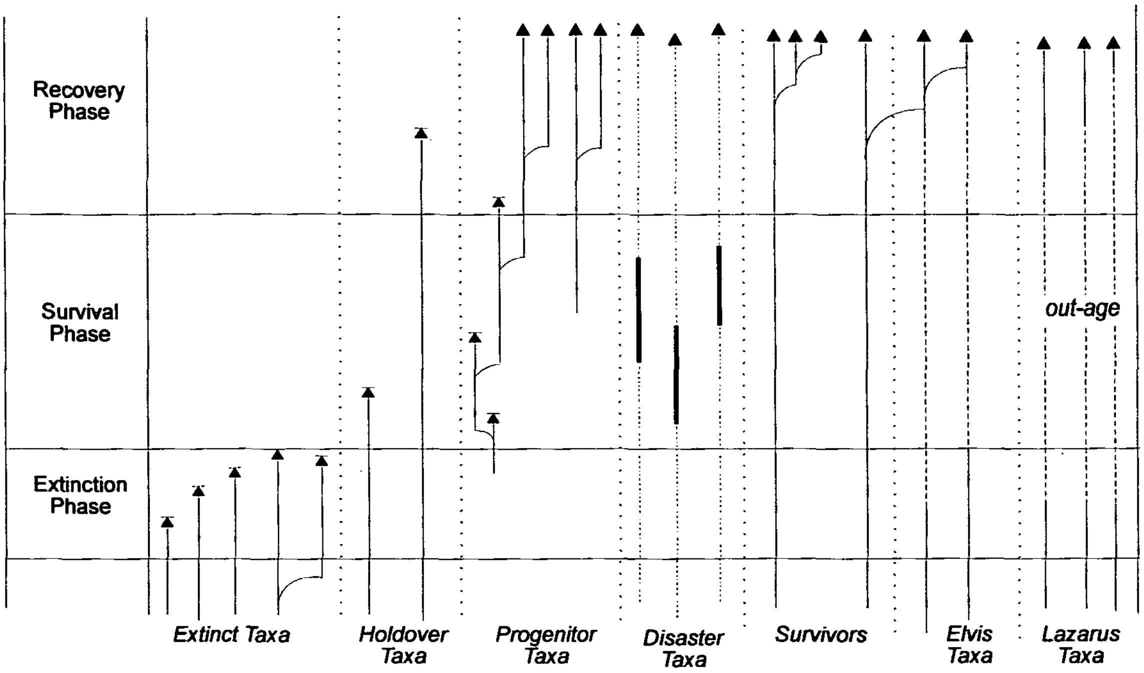


Figure 2. Generalised model showing typical phases and the range of responses of species during and after a mass extinction. From Hallam & Wignall (1997). Dotted lines - inferred range or occurrences; solid lines - observed range or occurrences

Holdover taxa outlive the majority of their clade but become extinct during a later interval.

Progenitor taxa enter the extinction / recovery game "a minute before the crisis", they are usually very successful during the later recovery competition.

Disaster taxa are pre-accommodated to catastrophic situations; abundant, R-strategic and often dwarf populations are allowed to rise during the developing environmental crisis. Uncommon before the mass extinction, but quite abundant locally during a crisis, they may occasionally enter the recovery interval.

Lazarus taxa: Re-appearing taxa that had disappeared from the fossil record during the extinction phase. Many different mechanisms have been proposed to explain this occurrence including the use of *refugia* and more simply, a decline in population size at times of extinction resulting in rare fossils (Jablonski, 1986; Kauffman & Erwin, 1995).

Elvis taxa: Proposed as an alternative mechanism to produce 'Lazarus taxa', thought to be the result of convergent evolution with younger taxa exhibiting homoplasy, hence they are 'Elvis impersonators who have appeared since the death of the King' (Hallam & Wignall, 1997, p15).

The recovery interval is marked by the radiation of both progenitors and the taxa that survived the mass extinction.

1.1.2 The IGCP Project 335 'Biotic Recovery from Mass Extinction Events'

Continued work on the patterns and effects of extinction events revealed a more and more complex set of environmental and biotic processes operating. In order to bring together researchers from a range of fields, from palaeontology to biology, two projects were set up under the broad umbrella of the IGCP. Project 335, Biotic Recovery from Mass Extinction

Events, was the successor to the highly successful IGCP 216 Global Bioevents. It was initiated in 1993, lead by Dr Doug Erwin (Smithsonian Institution, Washington D.C., USA) and Dr Erle Kauffman (University of Colorado, Boulder, Colorado, USA). The earlier completion of IGCP 216 "Global Bioevents" provided several conclusions about the significance of extinction processes (Walliser 1986):

- Extinction is very important for evolution, at least as important as biological innovation.
- Extinction creates large numbers of potential empty niches.
- Frequency of empty niches is positively influenced by the rise of evolutionary rate, while a negative correlation is found when selective pressure is increased.
- The rise of evolutionary rate leads, after a short time, to intensive diversification.
- Gradual evolutionary radiation leads to occupation of niches and, consequently, to the decrease of evolutionary rate with a resulting increase in selective pressure.

With the subsequent initiation of IGCP 335 "Biotic Recovery from Mass Extinction Events" the debate over the causes, and effects, of mass extinctions continued, but this time focusing on the question of how whole groups of organisms may reflect extinction and recovery intervals. The principle objectives of this project were to (Kauffman & Erwin 1995):

- establish international, high resolution, physical, geochemical and palaeobiological databases for survival and ecosystem recovery intervals following mass extinction;
- analyse evolutionary/ecological strategies and habitats that allowed lineages to survive mass extinctions and initiate subsequent biotic recoveries;

- analyse rates, patterns, biogeographical and environmental conditions of recovery following mass extinction;
- compare survival and recovery patterns from many mass extinctions and develop general models for extinction-survival-recovery processes; and
- develop predictive models to help us understand the probable aftermath of modern environmental deterioration and its associated biodiversity crisis.

Many papers were published resulting from project meetings at the University of Plymouth, 3-11 September 1994 and the final meeting in Prague, Czech Republic, 1997. The meeting at Plymouth resulted in the publication of the volume 'Biotic Recoveries from Mass Extinction Events' (Hart, 1996) containing a collection of papers that present the current state of knowledge on floral/faunal recovery following some of the global bioevents recognised and discussed during IGCP 216. Preliminary results from an analysis of foraminiferal diversity changes in faunas from the south Dorset Coast were also presented at the final meeting of IGCP 335 (Hylton, 1997).

1.2 Environmental change during the Early Jurassic

The extent of epicontinental seas in the latest Triassic and earliest Jurassic was very restricted as a consequence of the relatively low sea-level stand at that time (Hesselbo and Jenkyns, 1998). During Hettangian times a broad shallow marine shelf sea was established over most of Britain and north-west Europe, colonised by a low but gradually increasing diversity fauna (See Fig. 6), related to the major transgressive pulse at the base of the Jurassic. Imposed upon this general trend of sea-level rise, with major pulses in the early Hettangian, early Sinemurian, early Pliensbachian and early Toarcian, were episodic falls

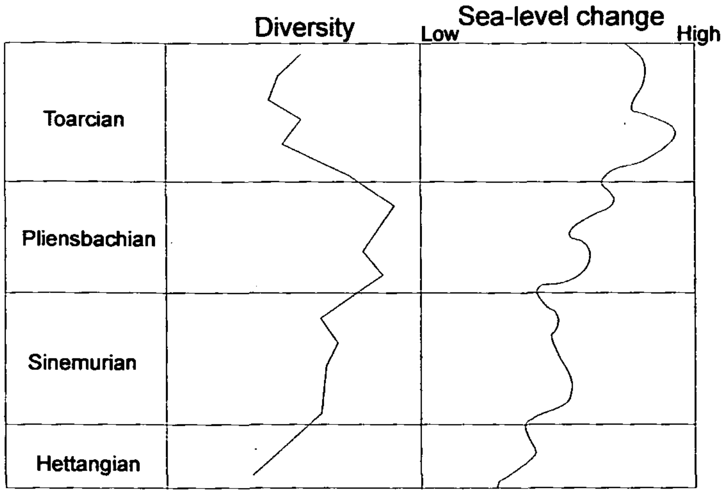


Figure 3. Correlation of species diversity increase up the British Lower Jurassic succession, according to Hallam (1996).Species data comprises bivalves, ammonites, rhynchonellids, crinoids, foraminifera and ostracods.

of sea-level (Hesselbo and Jenkyns, 1998). In general through the Phanerozoic, inferred rises of sea-level appear to correlate with diversity increase of neritic organisms and falls with diversity decrease, in extreme cases culminating in mass extinctions. The implication is that consequential changes in neritic habitat area are the controlling factors (Figure 3).

Numerous extinction events can be discerned from the record of Jurassic ammonites, because they have a high rate of turnover compared with all other fossil groups and thereby provide the basis for a biostratigraphy. Ammonite species and genera define zones and stages often in a very clear-cut way, which involves complete extinction of the older taxa.

Because of provinciality, however, many if not most of such extinctions were only of regional extent, and ammonite extinctions were for the most part not reflected in the extinctions of other groups. Therefore, if the ammonite extinctions were the result of environmental perturbations, such perturbations could not have been of great significance for the marine biota as a whole. As discussed earlier, to qualify as a mass extinction, other groups besides ammonites should have disappeared from the stratigraphic record. Hallam's (1986) analysis of species diversity throughout the early Jurassic, of five important groups – the bivalves, rhynchonellid brachiopods, crinoids, foraminifera and ostracods – and generic diversity of the ammonites, reveals how a trend of gradually rising diversity through the Hettangian - Sinemurian and Pliensbachian was sharply reversed in the early Toarcian. While the macrofossil data used for this analysis was comprehensive, the microfossil data generally focused on a small number of index species, usually taken from the 'Stratigraphic Atlas' of Jenkins and Murray (1981, 1989). Hallam (1987) analysed two regional studies, for Great Britain (Copestake and Johnson, 1981) and the Paris Basin (Bizon and Oertli, 1961), comprising ranges of 54 and 28 species respectively. In an updated analysis using the foraminiferal range data from the Stratigraphical Atlas of

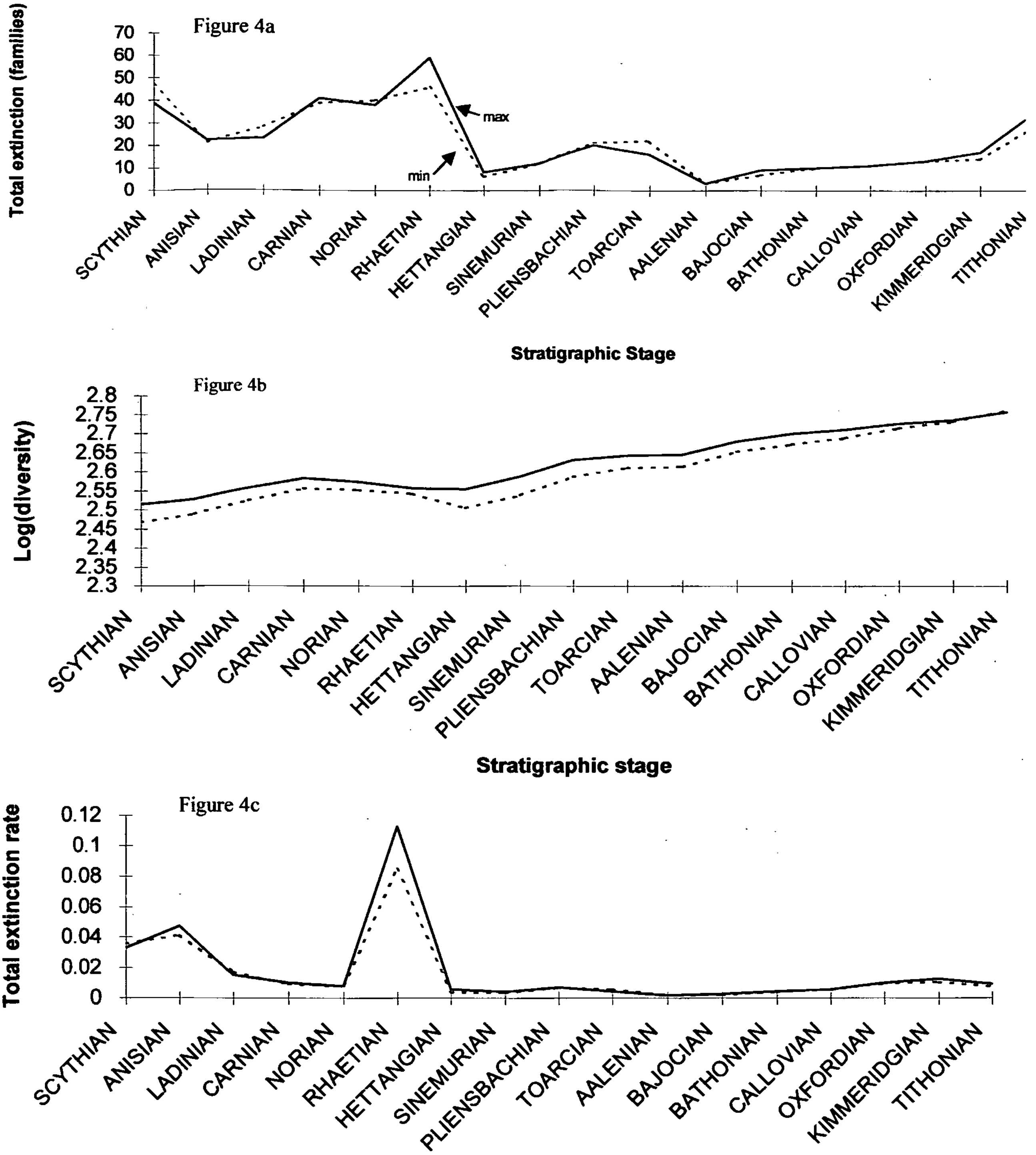


Figure 4. a) Pattern of family extinctions during the Triassic and Jurassic for marine organisms in terms of the numbers that died out in each stage. Maximum and minimum curves are shown. b) Patterns of the diversification of marine organisms during the Triassic and Jurassic plotted as a logarithm of diversity. Maximum and minimum curves as Figure 4a. c) Patterns of family extinctions during the Triassic and Jurassic for marine organisms in terms of the total extinction rate, that is, the numbers of families that died out in relation to the duration of each stage. Maximum and minimum curves as for Figure 4a. Data for all curves are from Benton (1993).

Jenkins and Murray (1989), Hallam (1996) and Hallam and Wignall (1997) figured diversity plots of some 75 species and sub-species of index foraminifera. While these plots indicate some adventitious fluctuations in species diversity during the Lower Jurassic and especially during the early Toarcian interval, they do not give a true representation of the diversity of the foraminifera of this interval. Combining the data of Johnson (1975) and Copestake (1978), gives a total of 304 species and subspecies for the Lower Jurassic (See section 1.3.2) and a more representative indication of the changes in foraminiferal diversity across the Pliensbachian - Toarcian boundary (Section 1.3.2, Figure 7a).

Benton (1993) made a recent reassessment of the changes in diversity for the whole of the Phanerozoic. Examination of the diversity and rates of origination and extinction through the Triassic and Jurassic (Figure 4a to 4c) show a high rate of extinction at the Pliensbachian - Toarcian boundary.

1.2.1 The Pliensbachian - Toarcian Boundary

Through their analysis of extinction periodicity, based on family-level data of marine extinctions, Raup and Sepkoski (1984, 1986; Sepkoski and Raup, 1986) claim to have recognised two events in the Jurassic, at about the end of the Pliensbachian and Tithonian stages; Sepkoski's (1992) update confirms the former event across the Pliensbachian - Toarcian boundary. While of lesser significance than the 'big five' Phanerozoic extinction events, they provide key data for the periodicity hypothesis and accordingly must be considered in some detail. This analysis was at the stage level of resolution and based on the recognition of a clear-cut extinction event in Western Europe (Hallam, 1986, 1987), the event was reassessed as probably taking place in the Lower Toarcian. Little's (1996) subsequent detailed sampling of invertebrate macrofaunas through sequences in north-west Europe confirms that most species extinctions occurred in the early Toarcian, following a regional anoxic event during Toarcian *falciferum* Zone times. This is not, however, equivalent to the supposed Pliensbachian - Toarcian event. There is, consequently, no evidence for a single family-level mass-extinction event at the end of the Pliensbachian stage (Sepkoski, 1989, 1990). Rather, there is a five-zone phase of extinction from the late Pliensbachian to early Toarcian with a significant species-level extinction event in north-western European sections caused by a regional oceanic anoxic event during early Toarcian *falciferum* Zone time (Hallam, 1986; Jenkyns, 1988).

1.2.2 Early Toarcian Oceanic Anoxic Event in western Europe

Sea-level rise across the Pliensbachian - Toarcian boundary culminates in the *falciferum* Zone of the Toarcian and is one of the best authenticated eustatic events in the Jurassic (Hallam, 1997). This major transgressive pulse is marked by evident deepening in marine sequences in geographically widespread parts of the world (Hallam, 1987) and associated with the widespread deposition of organic-rich shales. Lower Toarcian organic-rich shales (*falciferum* Zone) have outcrops and subcrops in north-east Britain, Paris Basin, Aquitaine, Spain (Borrego *et al.*, 1996; Jenkyns & Clayton, 1997) northern and southern Germany, Switzerland and elsewhere; several well known and characteristic exposures are shown in Figure 5. All these areas were flooded by early Jurassic epicontinental seas (Hallam, 1975). The organic-rich sediments are variously known as Jet Rock, Bituminous Shales, Schistes Cartons and Posidonienschiefer. Riegraf (1985) interprets the depositional environment of the Central European Posidonienschiefer as a large shallow marginal sea with a water depth of about 20 to 50 metres and warm, occasionally hypersaline water.

The thickness of these facies is generally in the range of 5-30m and the more organic-rich sediments are dark, millimetre-laminated, benthos-poor and contain carbonate and pyritic concretions. Ammonites, belemnites, bivalves, fish scales and other vertebrate remains

Figure 5. Field photographs of N. W. European black shale units. a) Schistes cartons of south central France at Truc de Balduc. b) Top of the Marlstone Rock Bed at Tilton Railway Cutting, Leicestershire. c) Laminated 'paper' shales of the *exaratum* Subzone at Tilton. d) SW German Posidonienschiefer of the Dotternhausen quarries, *bifrons* Zone, lower limestone is the Inoceramenbank. e) Posidonienschiefer with the characteristic limestone bands of the Unterer Stein, *falciferum* Zone. f) The Jet Rock of the North Yorkshire Coast at Port Mulgrave, just visible in the foreground are the Curling Stone Doggers.

dominate the macrofauna; the microfauna includes ostracods, foraminifera and radiolarians. Coccoliths, other calcareous nannofossils and dinoflagellates are locally abundant. The works of Kauffman (1978, 1981) and Seilacher (1982) exemplif y the differing and controversial interpretations of the palaeoecology of these facies.

These sediments are stratigraphically under- and overlain by non-bituminous argillaceous facies. Palaeontological control is good in most outcrops and, within the limits of current stratigraphical resolution, the deposition of the most organic-rich unit (lower *falciferum* Zone or *exaratum* Subzone) can be shown to be synchronous across northern Europe (Jenkyns, 1985, 1988). The depositional context of these sediments is thought to have been an oxygen-depleted epicontinental sea of moderate depth (Hallam, 1975). Jenkyns (1988) recognised that this period corresponded with high rates of carbon burial and a sharp positive excursion in the carbon isotope curve, signifying the Early Toarcian Oceanic Anoxic Event. This event coincides with a notable period of mass extinction of the marine fauna.

Sampling of invertebrate macrofaunas through complete (expanded) sequences in N. W. Europe has shown that most species extinctions occurred in the Early Toarcian following this regional anoxic event (Little and Benton, 1995). Little (1996) has documented the macrofaunal changes associated with this extinction event and the order in which new taxa appear in the recovery phase with the conclusion that survivorship across the extinction event shows patterns of selectivity by lifestyle with a gradient of extinction from infaunal benthos to epifaunal benthos to nektonic belemnites, ammonites and pseudoplanktonic crinoids. This pattern is consistent with that expected from a long period of anoxia.

1.2.3 Global turnover and recovery

The extinction event, first recognised by Hallam (1961, 1967a), led to an almost complete species turnover among the benthos during the *falciferum* Zone and was thought to have been only regional in extent. More recent work suggests, however, that it was of global significance affecting not just north west Europe but the south-western Tethyan realm and South American Andean basins as well (Riccardi *et al.,* 1990; Bartolini *et al.,* 1992; Nini *et al.,* 1995; Aberhan and Fürsich, 1997). Lower Toarcian black shales are reported from northern Siberia by Nikitenko & Shurygin (1992a) with corresponding changes in the macro- and microbenthos. The renewal of assemblages also took place at the beginning of the *falciferum* Zone.

Lower Toarcian organic-rich shales have recently been reported in the South Tethyan domain and considerable attention has been paid to the effects of low oxygen conditions in the south western Tethyan Umbria-Marche region of central Italy where black shales are extensively developed across the Pliensbachian-Toarcian boundary (Bartolini *et al.,* 1992; Nini *et al.,* 1995; Jiménez *et al.,* 1996; Parisi *et al.,* 1996). The shales are seen as being indicative of a spreading oxygen deficiency from the lowest part of the *tenuicostatum* Zone. Across the boundary, Nini *et al.* (1995) found that the large Pliensbachian Lagenina were replaced by a small-sized assemblage dominated by *Paralingulina* gr. *tenera* (≈*Lingulina tenera* plexus), characteristic of black shale facies.

Faunal turnover across the Pliensbachian - Toarcian boundary and during the early Toarcian would appear, therefore, to be caused by anoxia in north west Europe. Other non-European studies have shown changes in diversity, which are not associated with anoxia. Aberhan and Fürsich (1997) have shown that marine bivalves of the Andean Basin of southern South America exhibit a marked decrease in diversity across the boundary. This change occurs in well-aerated shelf environments so oxygen deficiency cannot be the sole cause, as it seems to be in European epicontinental seas. Consequently, Aberhan and Fürsich assume that sea-level change and the resulting oceanographic and biotic changes were the controlling factors of species diversity patterns. Also in the Andean Basin, the distribution charts of foraminifera and ostracods suggest a strong faunal turnover and reduction in diversity across the Pliensbachian - Toarcian boundary (Ballent *in* Riccardi *et al.*, 1990). It is advised, however, that these data be viewed with caution as the Argentinean Toarcian sediments may not be a suitable facies for microfossil collection (Aberhan and Fürsich, 1997). The event is thought to have a global distribution because, although the majority of the family extinctions occurred within Boreal north-western Europe, there were also extinctions in the Tethyan and Austral realms (Benton & Little, 1995).

1.3 Lower Jurassic foraminiferal research

1.3.1 History of Lower Jurassic foraminiferal investigation and classification

Lower Jurassic foraminifera were dominantly of benthonic habit. Unquestionably planktonic species are not recorded until the Middle Jurassic (Late Bajocian) with possible ancestral species described from the Toarcian sediments of Europe (See debate in Simmons *et al.*, 1997). However, many benthonic species show very consistent stratigraphic ranges over wide geographical areas (Copestake, 1985) and, consequently, this group is of great value in subdividing and correlating the Lower Jurassic; stratigraphically distinctive microfossils being of great importance in situations where ammonites are not recovered. In the study of ecological collapse and the cause of mass extinctions, the fact that foraminifera 'are the most abundant marine invertebrates and play a major role in the economy of nature' (Haynes, 1990, p.503) adds to their significance. From the first known appearance of foraminifera in the Cambrian, generic diversity has shown a general increase, although with major extinctions at certain intervals. A fairly steady increase in total diversity also

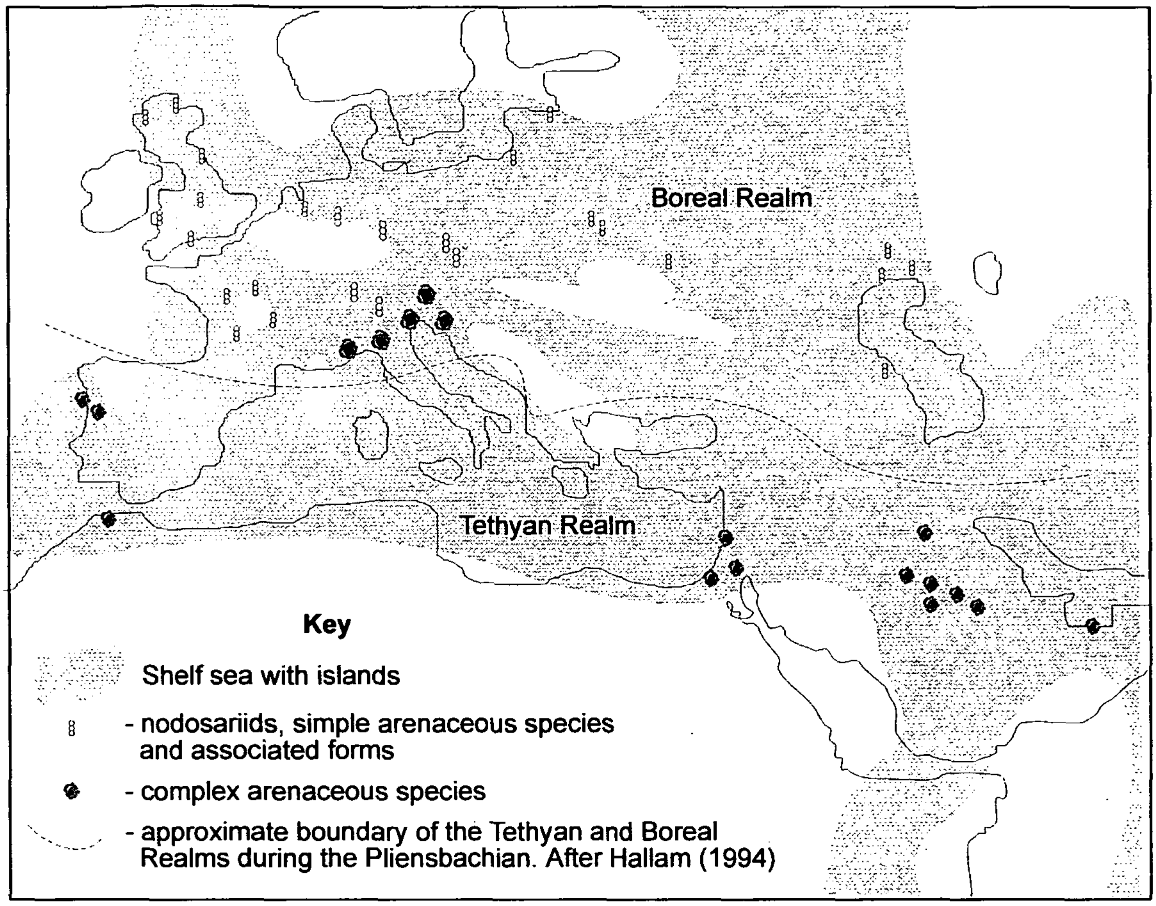


Figure 6. Distribution of types of Lower Jurassic assemblages of foraminifera in Europe and the Middle East. After Gordon (1970). N. W. European assemblages are composed of smaller calcareous foraminifera, dominated by nodosariids (group A of Gordon, 1970). In northern Europe and Arctic regions this fauna is replaced and dominated by agglutinating foraminifera, as described from Svalbard (Løfaldi and Nagy, 1980). In the Mediterranean areas (southern Europe and Africa) and Middle East a Tethyan realm of carbonate deposition was dominated by large, complex-walled agglutinating foraminifera (group B of Gordon, 1970). South of this warm-water belt, however, assemblages comparable to western Europe have been described from Algeria (Maupin and Vila, 1976), and offshore Morocco (Riegraf *et al.*, 1984). Recent research shows that Lower Jurassic foraminifera of western European type (group A of Gordon, 1970) are widespread in the southern hemisphere, and have to date been reported from Papua New Guinea, Western Australia and Argentina (Quilty, 1981; Ballent, 1987; Copestake & Johnson, 1989).

characterised the Mesozoic (Tappan and Loeblich, 1988a). At the end of the Triassic, major decreases occurred in the previously dominant Robertinina and Involutinina and about one-third of the Miliolina disappeared (Tappan and Loeblich, 1988). These suborders, by the Lower Jurassic, were surpassed in importance by the rapidly diversifying Lagenina and, to a lesser extent, the Textulariina.

Elevated, interconnected continents, restricted seaways and transgressions in the Early Jurassic resulted in organic-rich facies extending into more marginal areas and the subsequent expansion of smaller benthic foraminifera (Gordon, 1970). Common in the dark clays of the Jurassic and Cretaceous, the flattened and elongate tests of the Lagenina were probably an adaptation to burrowing in the upper few centimetres of an organic-rich substrate, as detrital or bacterial scavengers (Tappan and Loeblich, 1988). As illustrated by Figure 6, the Boreal realm of the Lower Jurassic was dominated by a single family, the Nodosariidae, with lesser numbers of Miliolina, Robertinidae, Spirillinina, Involutinina, Buliminacea, Textulariina, Polymorphinidae and Cassidulinacea (Copestake and Johnson, 1989). The most common forms of nodosariids include species of *Dentalina*, *Frondicularia*, *Lingulina*, *Marginulina* and *Nodosaria*. Foraminifera other than nodosariids are principally arenaceous forms, including *Ammodiscus*, *Trochammina* and *Reophax*.

The foraminifera of the Lower Jurassic have been the subject of extensive research spanning over 150 years with more than three-quarters of the literature concerned with faunas from Europe north of the Alps (Gordon, 1970). Among the early papers there are four of interest as they are well illustrated and deal with foraminifera from the Lower Jurassic. They are the works of Jones & Parker (1860), Brady (1867), Blake (1876) and Crick & Sherborn (1891). Most important of these early works was that of Blake (in Tate and Blake, 1876) on the Yorkshire Lias, since a considerable number of species are figured and indications are given of their stratigraphic distribution. Most of the forms described are from the Hettangian - Pliensbachian.

There were no great advances in the study of British foraminifera until Macfadyen (1941) and Barnard (1950a), on the Hettangian to Lower Pliensbachian of the Dorset coast and Barnard (1950b) on the Toarcian of Byfield (Northamptonshire). Macfadyen solved several taxonomic problems, whilst Barnard first applied the "plexus concept" to Jurassic foraminifera; an approach he continued to pursue in several subsequent works (Barnard, 1956, 1957, 1960). These authors were among the first to grasp the problem of intraspecific variation in Jurassic foraminifera and Adams (1957) further explored this aspect in the case of Toarcian microfaunas from Lincolnshire.

Foreign literature is very varied, but falls into two well-marked divisions of the French and German schools. The German school contributed three main works: Bornemann (1854), Franke (1936) and Bartenstein & Brandt (1937). Bornemann (1854) gives a good clear account of the fauna from the Lower Jurassic of Göttingen and described a number of new species. Franke (1936) continued the study of Lower Jurassic foraminifera, creating a large number of new species and a lengthy nomenclature. Bartenstein and Brand's (1937) paper, which attempts to zone the Lower Jurassic, is an important work, following Cushman's (1925) classification.

D'Orbigny (1849) initiated the French school. Macfadyen (1936), who came to the conclusion that a large number of species were insufficiently described, revised his work. At about the same time that d'Orbigny was publishing descriptions of his Lower Jurassic foraminifera, Terquem (1858-1874) produced a series of memoirs, in which he included a very large number of species. Macfadyen (1941) and others questioned the validity of Terquem's work, as it was responsible for much of the taxonomic confusion regarding Jurassic foraminifera due to the poor quality of his figures and descriptions. As a result of this history of confusion, over 800 species of benthic foraminifera have been described from the Lower Jurassic successions of western Europe (Brouwer, 1969) with many conflicting species descriptions, leading to a confusion of taxonomy and diminished use of them as biostratigraphic markers. Indeed, Loeblich and Tappan (1988a) have regularly revised their foraminiferal taxonomic classification schemes since the publication of Loeblich and Tappan's (1964) Treatise volume including the most recent re-description of foraminiferal genera. Haynes (1990) highlights a number of problems with the treatment of suborders in the Treatise (Loeblich and Tappan, 1964) including the Lagenina where the diagnoses made do not make a distinction between the Nodosariidae and Vaginulinidae because both can include arcuate to uncoiled genera. The subfamily Marginulininae also can not be distinguished from the Vaginulininae on the diagnoses given. In a slightly modified classification, Copestake (1978) emends the Vaginulininae to include curved genera only while the Marginulininae is included within the Lenticulininae comprising coiled forms (See Chapter 3).

1.3.2 Recent research

The most complete Lower Jurassic sequence studied for foraminifera in the UK was cored in the Llanbedr (Mochras Farm) borehole, north Wales, between 1966 and 1969 (Woodland, 1971). Johnson (1975) studied the foraminifera of the Upper Pliensbachian and Toarcian with the Hettangian to Lower Pliensbachian section being completed by Copestake (1978). These two works, although remaining largely unpublished, contain a considerable amount of information that has been compiled by the author.

The Mochras borehole foraminiferal fauna in Figure 7a shows distinct changes in assemblages across the Pliensbachian - Toarcian boundary and within the basal zone of the

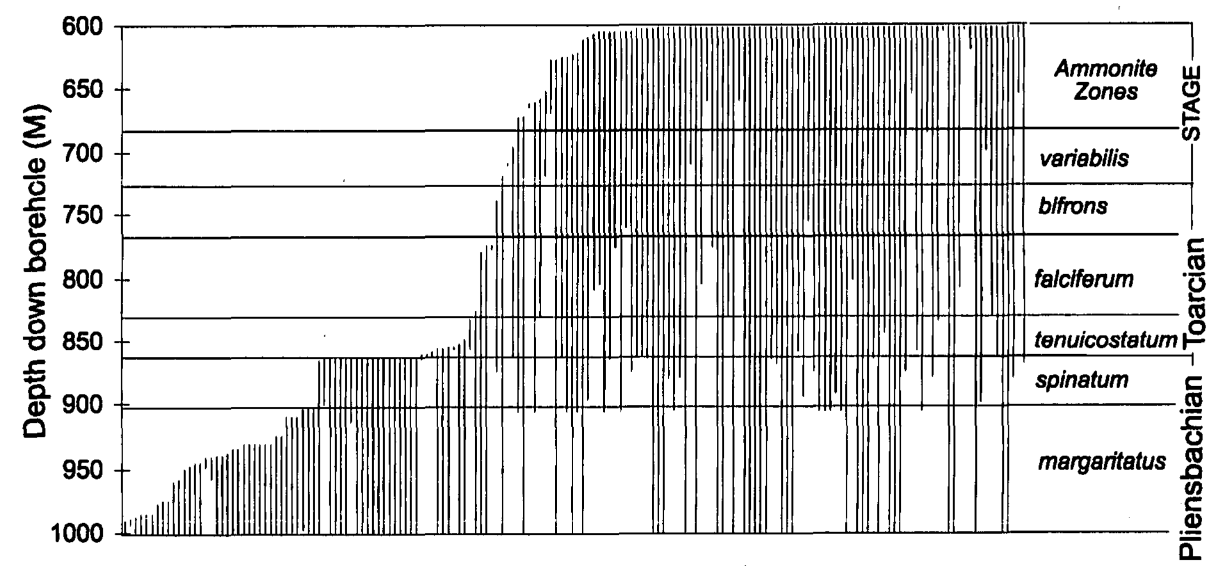


Figure 7a. Benthic foraminiferal ragnes from the Mochras Borehole, Wales, UK. Ranges compiled from Johnson (1975) and Copestake (1978).

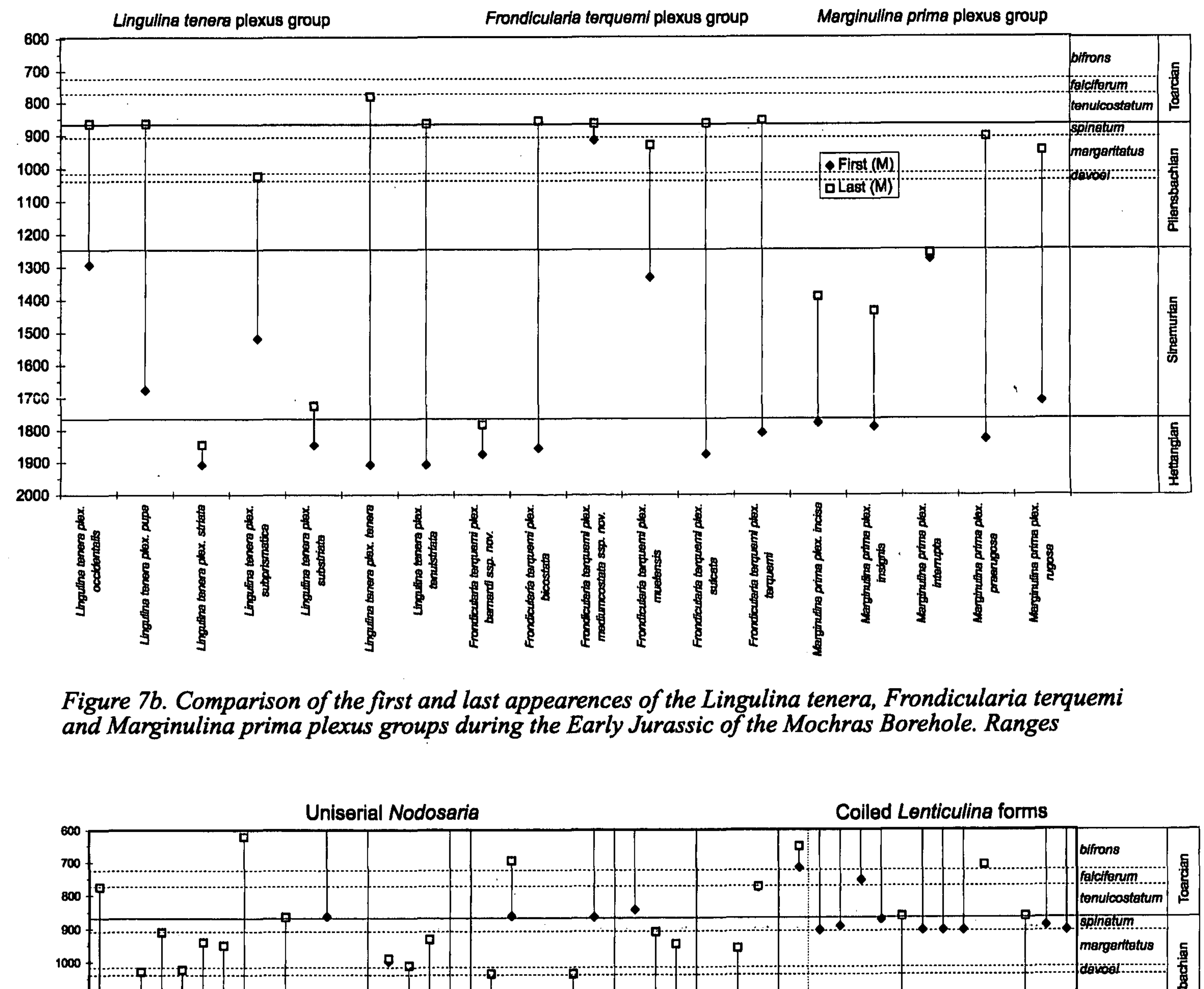


Figure 7b. Comparison of the first and last appearences of the Lingulina tenera, Frondicularia terquemi and Marginulina prima plexus groups during the Early Jurassic of the Mochras Borehole. Ranges

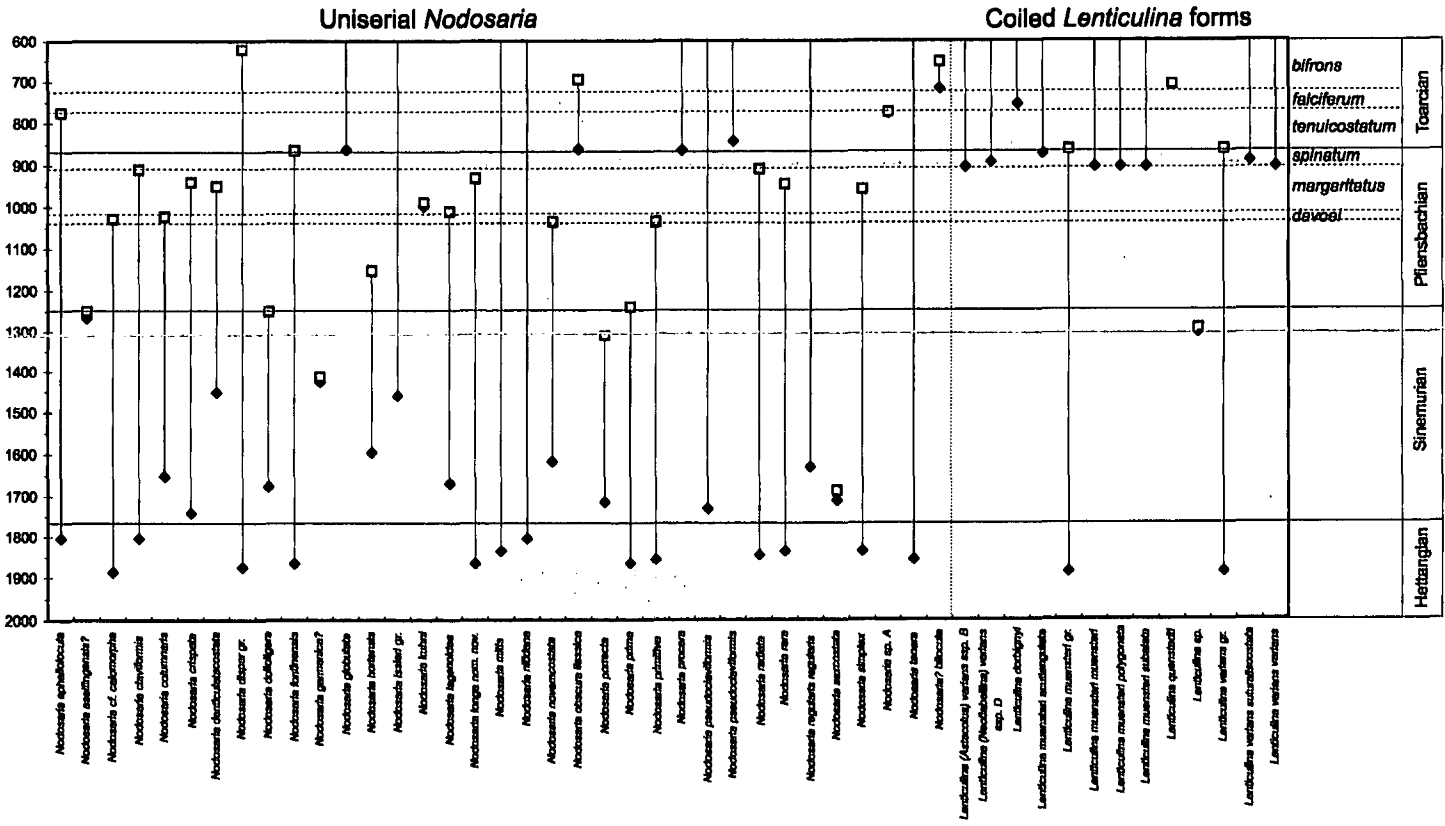


Figure 7c. Comparison of the first and last appearences of species of Nodosaria and Lenticulina, from the Mochras borehole. Ranges compiled from Johnson (1975) and Copestake (1978). Biostratigraphy from Woodland (1971).

Toarcian. During the *tenuicostatum* Zone the foraminifera show a decrease in diversity, as ecological stress developed and continued throughout the zone (Johnson, 1975).

The deepening marine water resulted in a reduction in bottom water circulation and this deepening trend reached its acme in the basal *exaratum* Subzone. The subsequent record of open normal marine conditions is absent by faulting, although the missing section is entirely within the *exaratum* Subzone (Johnson, 1975).

Brasier (1988) notes that while there is little available evidence for foraminiferal mass extinction events in the Lower Jurassic, certain groups were eliminated in boreal regions including the important Lower Jurassic *Lingulina tenera, Frondicularia terquemi* and *Marginulina prima* plexi. Also, there was a marked change in the chamber arrangement of younger nodosariid assemblages: the place of uniserial *Nodosaria, Frondicularia* and *Lingulina* were largely replaced by coiled *Lenticulina* (Copestake and Johnson, 1989). The Mochras borehole clearly reflects these changes, illustrated by Figures 7b and 7c.

As a result of a synthesis of the Mochras data with all previously published data, Copestake and Johnson (1984) and Copestake (1985), proposed a worldwide foraminiferal biozonation scheme for the whole of the Lower Jurassic. Copestake and Johnson (1989) using newer data and finer correlation with the ammonite zonation constructed a more detailed scheme, for the British Jurassic. Johnson (1975, 1976), who established some broad ranges for individual benthic foraminiferal species from the Mochras Borehole, also examined the palaeoecology of the Lower Jurassic foraminifera.

Norling (1972), in his study of the Jurassic stratigraphy and foraminifera of western Scania, southern Sweden, found a close correlation with north-west Germany and north-east England. The Pliensbachian transgression of north-western Europe extended over Scania resulting in a marine shelf environment and a fauna consisting predominantly of nodosariid foraminifera. Norling notes a difference in the foraminiferal faunas recovered from the Rydebäck Beds of Late Pliensbachian to Toarcian age. The fauna is diverse and abundant in the lower part but exhibits a significant decrease in the number of species and abundance in the upper part of this unit. New species also appear in the upper part and correlate to forms restricted to the Toarcian in north-west Europe.

Somewhat different foraminiferal faunas are found in the northern North Sea formations. Nagy (1985a, 1985b) analysed core samples of five wells in the Statfjord area and found an initial delta-influenced, marine-dominated fauna of *Dentalina* and *Nodosaria*. This fauna was followed by successive steps in the development of a delta system and a corresponding change in foraminiferal faunas, finally becoming dominated by an *Ammodiscus* assemblage of low diversity arenaceous forms ascribed to hyposaline delta front conditions.

Documentation of British microfaunas has continued with a brief description of the Lower Jurassic foraminifera from the Winterborne Kingston Borehole, Dorset (Coleman, 1982). Muller (1990), who used statistical analysis to propose thirteen biofacies groups and a palaeobathymetry model, explored palaeoecological aspects of British Liassic foraminifera.

The Lower Jurassic successions of Europe have been the focus of much research especially concerning the foraminiferal assemblages of Pliensbachian and Toarcian age. Riegraf (1985) using some 19 sections conducted one of the most comprehensive studies of the German Lower Jurassic. The details of the foraminiferal and ostracod faunas of the Posidonienschiefer were studied in great detail, revealing several levels of extinction within the early Toarcian interval. The Schistes Cartons of southern France was also sampled by Riegraf (1982, 1985) who identified a series of disappearances and reappearances of foraminiferal groups through the anoxic phase and the subsequent recovery.

Cubaynes & Ruget, (1983) describe a new species *Lenticulina [Marginulinopsis] pennensis,* from the middle Toarcian of north west Europe. Nicollin (1988) studied foraminifera collected from the Schiste Carton facies around Montgriffon (southern Jura) finding typically Toarcian assemblages and horizons rich in *Reinholdella* and *Spirillina,* suggesting particular ecological conditions. The Early Toarcian events were investigated by Nicollin & Ruget (1988) who note a period of change for benthic foraminifera in western Europe, especially for the nodosariids; a phenomenon expanded upon by Cubaynes & Ruget (1988), whose detailed analyses of the benthic foraminifera in the Grésigne area near Toulouse, led to the designation of two pioneer genera: *Lenticulina* and *Dentalina.* The importance of the nodosariids in Lower Jurassic stratigraphy is re-emphasised by Ruget (1988) with the proposal that although many species are long ranging, species assemblages are diagnostic of a stage or zone. Ruget, Cubaynes & Boutakiout (1988) then proposed foraminiferal biozonations for the middle Toarcian of Southern Quercy, defining five horizons based on cithinarinid faunas correlated with the ammonite zonation. Nikitenko & Shurygin (1992b) also propose a foraminiferal biozonation scheme for the Boreal Realm based upon the study of Lower and Middle Jurassic successions of the Russian Arctic. They describe a number of biostratigraphic markers within the biozones that correlate with sections in western Europe, as well as erecting parallel schemes for bivalves, foraminifera and ostracods. However, many of the index species used are not widely known in the literature or are described as different species by different authors. Also, the majority of the primary literature and data sources cited are in Russian.

The preceding discussion reveals some of the problems that arise when trying to correlate foraminiferal genera and species between different 'schools' of taxonomy. Consequently, attempting to define the response of foraminifera to the early Toarcian events, on a northwest European regional scale, is greatly complicated by the differing taxonomies of previous workers. The fact that there is little standardisation stems from problems with the classification of the foraminifera in general and, more specifically, the high degree of variability of species during the Lower Jurassic. This phenomenon often led to the erection of many new species names based upon slight morphological differences. Conversely, the other approach was to lump all variants of a species within one species name and consequently lose valuable palaeoecological and biostratigraphical data on those species. Species which contain a number of recognisable subspecies as well as many variants are well known from the Lower Jurassic (Copestake, 1978); e.g., *Lingulina tenera, Frondicularia terquemi, Marginulina prima.* These species show a progressive evolution through the Early Jurassic. In view of the wide range of morphotypes and the high degree of variation in these species, the term *species plexus* has been utilised for such cases (see Barnard, 1950a, 1956, 1957, 1960). Copestake (1978) defines the species plexus as a single, variable, polytypic species, which is evolving and has thus produced distinct subspecies, in addition to many variants, during the course of its development. The value of short-ranged morphological variants is enhanced by recognition of their place as subspecies (chronosubspecies) within the evolving plexus. Barnard (1956) suggested that certain trends produced during the evolution of a plexus might be due to changes in the environment. This proposal was supported by palaeoenvironmental data established on the different members of plexi recovered from the Mochras sequence (Johnson, 1975, 1976) where the interpreted ranges of the plexi indicated that each member occupied a slightly different environmental range. Unfortunately, the use of plexus groupings has largely been ignored in most studies, resulting in the loss of subtle palaeoenvironmental data at most levels.

Palaeoecological interpretations of Jurassic foraminiferal assemblages are also difficult to make owing to a lack of direct Recent analogues owing to drastic changes which took place in the nature of benthic shelf assemblages during the Cretaceous and Tertiary (Copestake & Johnson, 1989). These changes resulted in the replacement of nodosariids, which were dominant in the Jurassic (Gordon, 1970), by other families of Rotaliina; nodosariids in the modern day occupy a deeper water setting than in the Jurassic. It is necessary, therefore, to establish environmental data on individual Lower Jurassic fossil species so that finer and more accurate palaeoecological analyses can be made.

1.4 Synopsis of this study

The sedimentology, palaeontology and palaeogeography of the Lower Jurassic of north west Europe is well documented (e.g., Sellwood, 1972; Hallam, 1987; Warrington & Ivimey-Cook, 1995) and exposures in the United Kingdom and continental north-west Europe have provided an excellent opportunity to establish some ecological data on individual Lower Jurassic foraminiferal species. These data are essential for the analysis of the causes of the Toarcian extinction events and the subsequent biotic recovery.

1.4.1 Aims and objectives

The widespread development of dysoxic to anoxic waters is regarded as the principal cause of most marine extinctions (Hallam & Wignall, 1997 p250). Invariably such dysoxic/anoxic episodes are associated with sea-level rise and the anoxia-transgression link is one of the principal recurrent themes of the stratigraphic record (see, for example, Hallam, 1981a; Wignall, 1994).

In the Mesozoic many of the extinction events (e.g., Cenomanian - Turonian event: Jenkyns, 1985) are represented by organic rich sediments deposited under dysaerobic/anaerobic conditions occurring throughout N. W. Europe (Jenkyns, 1988) and the Lower Toarcian event, which is well exposed in the Jurassic successions of western Europe, has not yet been fully investigated for its microfauna.

This programme of research has concentrated on the study of the microfauna (Foraminifera, Ostracoda, holothurian sclerites, etc.) across the event while also looking at the pre-extinction faunal assemblages (e.g., Hylton, 1998, 1999). The main aim of the work is to trace the response of benthonic foraminifera to early Toarcian events through:

- High resolution sampling and study of fossiliferous sections in north west Europe, ranging from south west Germany, through France and southern England to the north Yorkshire coast.
- The independent correlation of the studied sections using the foraminiferal index species and data .
- Integration of microfaunal data with the current research on the causes and effects of the Toarcian mass extinction event.

Following from these objectives, this study aims to provide evidence and data on these wider areas of investigation:

- Does the foraminiferal fossil record provide support for the hypothesis of periodicity in extinction of marine families and genera, advanced by Raup and Sepkoski (1984, 1986), Sepkoski and Raup (1986)?
- What information does the Lower Jurassic foraminiferal fossil record provide on the rates of change and ecological effects of the Toarcian extinction event?
- Does the foraminiferal data lend support to sea level forcing of adaptive radiations and extinctions? Conversely does falling sea level cause partial or complete collapse?

- How does the microfaunal response to the events discussed correlate with the macrofaunal response?

Early Jurassic oceanic anoxia, extinction events, the deposition of organic-rich sediments and sea-level changes continue to be the subjects of ongoing research (Little, 1996; Hallam, 1997; Jenkyns and Clayton, 1997). This study is ideally placed to make a significant contribution to the understanding of the processes affecting the foraminifera and microfauna of this part of the Jurassic while providing a useful database for future research and stratigraphic correlation.

Chapter 2 Methodologies

2.1 Introduction

2.1.2 The study of extinction events

Global analyses of extinctions and radiations at the taxonomic level of family and stratigraphic level of stage, while very desirable for a preliminary survey, are increasingly regarded as being too coarse-grained to resolve many of the critical questions that have been posed (Hallam, 1987). Also, individual outcrop studies, because of their restricted geographic and taxonomic scope, offer little to an analysis of regional magnitude and breadth of an extinction event.

Holland (1995) notes that palaeobiological and biostratigraphical studies depending upon the stratigraphic distribution of fossils can suffer from hidden biases. Particularly prone to this problem are studies that emphasise morphological or taxonomical changes or patterns of first and last occurrences in single sections of strata or that focus on several geographically close sections, because the effects of facies control will be most severe at these geographically restricted scales. Facies control can be greatly reduced by expanding a study to include several sections spanning the range of facies along a palaeobathymetric transect. In this way, progressively shallower or deeper facies would be encountered and the biasing effects of facies control on the vertical distribution of a taxon can be accounted for. Careful and rigorous comparisons between outcrops are required for analyses of the duration and detailed temporal pattern of extinction. However, complete stratigraphic records of mass extinction or other intervals are thought to be quite rare (Dingus, 1984), complicated by the fact that many mass extinctions occur at falling or fluctuating sea

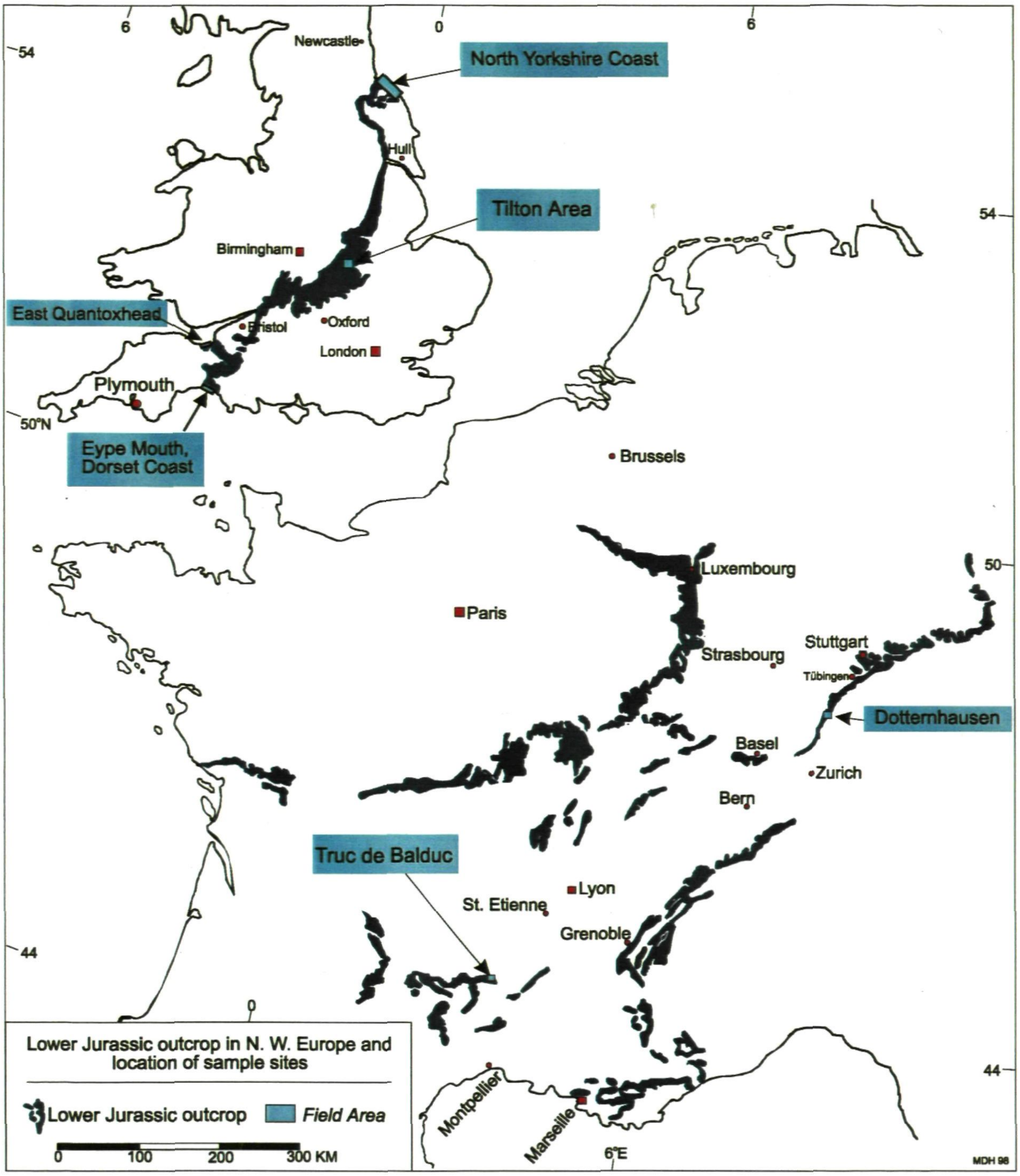


Figure 8. Lower Jurassic outcrop of north-west Europe with location of successions investigated in this study: Truc de Balduc, near Mende, Département Lozère; Rohrbach Zement Quarry in Dotternhausen near Balingen, SW Germany; Eype Mouth and Watton Cliff near Bridport, south Dorset Coast; East Quantoxhead, north Somerset Coast; Tilton Railway Cutting and Brown's Hill Quarry near Melton Mowbray, Leicestershire; North Yorkshire Coast, Staithes to Port Mulgrave, Robin Hood's Bay and Ravenscar.

levels, enhancing non-deposition, restriction, or erosion of epicontinental and continental marginal marine sections (Kauffman, 1986).

The marine Lower Jurassic of north-west Europe (Figure 8) is particularly well suited to this kind of study. Numerous workers have studied its sequence of richly fossiliferous strata over many decades and the biostratigraphic zonation derived from the ammonite sequence allows time resolution as refined as any that has been achieved for the Phanerozoic. There has been much taxonomic work on a wide range of invertebrate groups, as well as facies analysis of the strata and the size of the region in question, on the order of a million square miles, is large enough to enable events of merely local significance to be eliminated from consideration.

For this study, all accessible sections in the United Kingdom were assessed for stratigraphical completeness and the suitability of their facies for micropalaeontological potential. Continental European sections were also required, in order to gain the geographic breadth required to assess the regional effects of the Toarcian events on the microfauna. Data for this study has been sought at regional, species (or at least generic) and zonal levels. Full attention has been paid to the intervals before the extinction events in order to place the latter into a well understood temporal context of "normality".

2.2 Sampling programme

2.2.1 Stratigraphic and sampling considerations

The investigation of extinction events has long been plagued by artificial patterns resulting from the effects of sampling. Signor and Lipps (1982) showed that even sudden extinctions may appear gradual as sampling efficiency declines near the boundary. Holland (1995) and Jablonski (1980, 1985) also contend that paleobiological patterns in the stratigraphic record can rarely be accepted at face value. As discussed in the previous section, the combined effects of sampling, facies control and cyclic facies changes on the fossil record are rarely taken into consideration when studying such palaeobiological patterns. A second sampling consideration asks how representative of a locality is a single sample? Buzas (1990) suggests that replicate samples are required to estimate species proportions at a locality.

Several sections in the United Kingdom and north-west Europe have consequently been investigated with regard to their microfossil potential. The aim has been to collect a comprehensive set of samples of suitable lithologies (clays, mudstones, shales) from accessible Pliensbachian-Toarcian sections. These samples have been stratigraphically located as accurately as possible. The Lower Jurassic has a sophisticated zonation scheme and most sections can be zoned with reasonable accuracy. The ammonite zonal system of Cope et al., (1980) for the British Isles was employed in this study as it includes, and correlates, all the sections sampled. The details of all localities are listed below; Figure 8 shows the outcrop distribution of the Lower Jurassic in north west Europe, together with the location of the sampled sections while Figure 9 contrasts the zonal thicknesses and completeness of the chosen sections.

2.2.2 Chronostratigraphy

2.2.2.3 Definition of European Lower Jurassic

The Lower Jurassic comprises the Hettangian, Sinemurian, Pliensbachian and Toarcian stages, considered to span a period of 30 million years (Harland *et al.*, 1990) and is represented lithostratigraphically by predominantly argillaceous rocks commonly referred to as the *Lias* or *Lias Group* (Powell, 1984). Traditionally, the Lias Group has been subdivided into the Lower, Middle and Upper Lias, terms which have been persistently used in a chronostratigraphic sense, equating with the Hettangian - Lower Pliensbachian, the Pliensbachian - Early Toarcian crisis (185.7+0.6/-0.8 Ma to 181.4±1.2 Ma), zonal

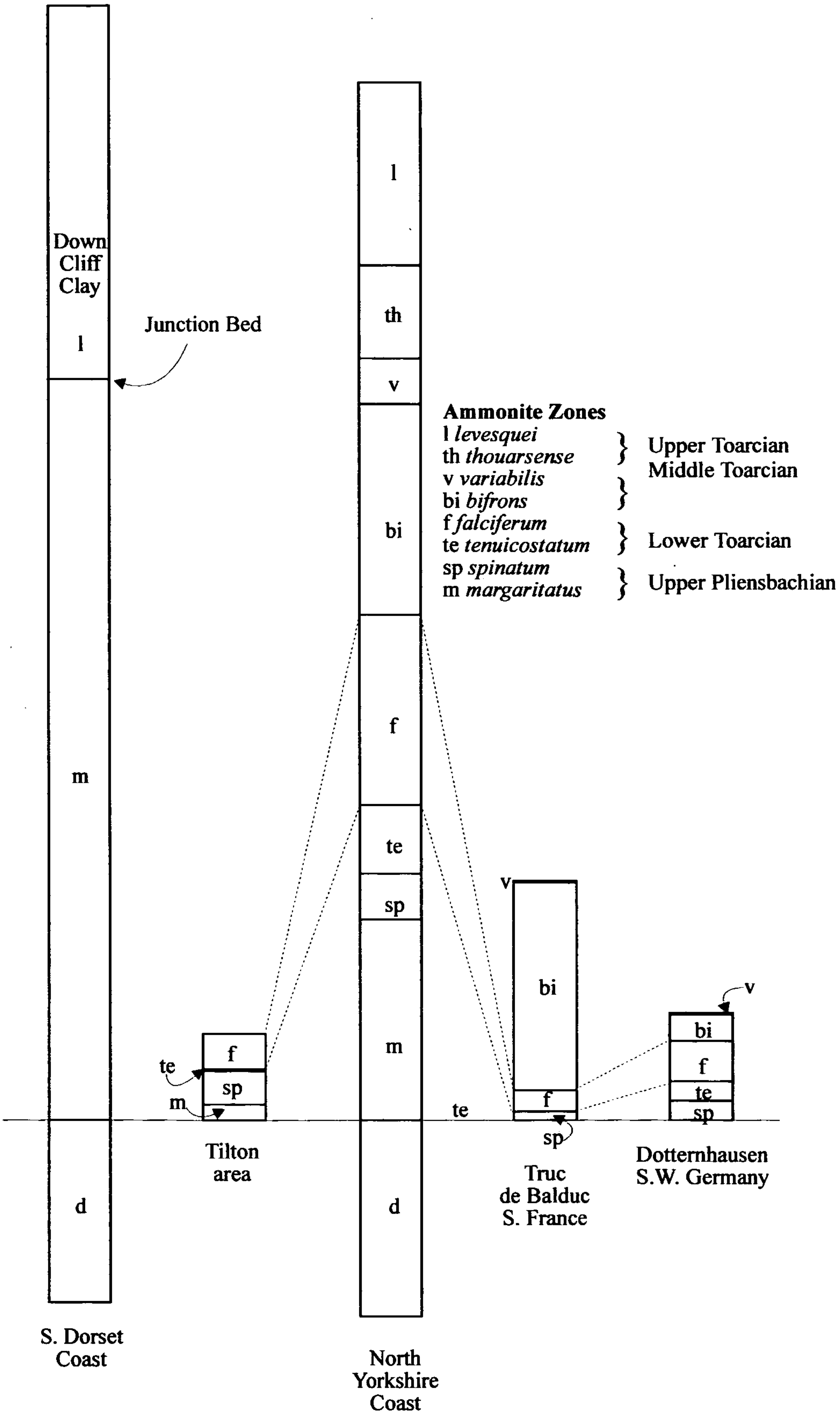


Figure 9. Comparative sections in the Lower Jurassic of north west Europe. The vertical sections given have been compiled from the following sources and have been modified to conform with the zonal scheme used in Cope et al. (1981). Dorset and North Yorkshire Coast: Woodland (1971); Tilton area: Cope et al. (1981); Truc de Balduc and Dotternhausen: Riegraf (1985).

durations Upper Pliensbachian and the Toarcian respectively. As the terms 'Lower', 'Middle' and 'Upper' are not acceptable as formal lithostratigraphic subdivisions (Salvador, 1994: p40), the use of Lower, Middle and Upper Lias is no longer recommended. While Powell (1984) introduced a new lithostratigraphical nomenclature for the Lias Group in the Yorkshire Basin, for the rest of Britain and Europe, many old informal and conflicting names are still in use. For example, the term *Lias* has, in the past, been used in Britain in either a lithostratigraphical sense, for the argillaceous sediments above the calcareous White Lias at the top of the 'Rhaetic Beds', or in a chronostratigraphical sense equivalent to Lower Jurassic, as in the classical continental European divisions of the Jurassic into Lias, Dogger and Malm (Callomon & Cope, 1995). The Middle Lias, however, when used in a purely lithostratigraphical sense corresponds (in Britain) approximately to the upper Domerian Substage of the Pliensbachian, unlike the use in continental Europe, where it encompasses the whole of the Pliensbachian.

In order to resolve the conflicts in the use of differing terms in this study, given its pan-European nature, Lias, as a formal term is not used and lower Lias refers to an informal lithostratigraphic subdivision of the Lias Group (cf. Powell, 1984).

2.2.2.4 Correlation and Ammonite Zonation schemes

Formulating and testing models of biotic recovery following mass extinctions requires accurate calibration of chronostratigraphical and numerical time scales. One of the most important considerations when undertaking a study of this kind is correlation between sections in different regions and the maximum resolution of that correlation must be considered (Little & Benton, 1996). As with all biostratigraphic schemes, there are problems of palaeobiogeographical provinciality. During the Pliensbachian and Toarcian stages, ammonite faunas were roughly separated into the northern Boreal Realm and the southern Tethyan Realm (Hallam, 1975; Smith and Tipper, 1986). Shared and immigrant genera allow correlation between realms, but only to the zonal level of timescales of perhaps 1 m.y. The fact that all Lower Jurassic oceanic crust has been subducted, coupled with absence of extrusive igneous rocks in the marine Pliensbachian - Toarcian section, makes magnetostratigraphic correlation problematic. Until recently, isotopic records (K-Ar, Rb-Sr, etc.) for the Pliensbachian and Toarcian stages were extremely poor until a new U-Pb age from the Middle Toarcian of North America was calculated by Palfy *et al.,* (1997) as 181.4±1.2 Ma. At present, correlation can best be achieved using the excellent biostratigraphical scheme, first developed by Quenstedt and others over 130 years ago, for the European Jurassic (Dean *et al.*, 1961; Haq *et al.*, 1988; Harland *et al.*, 1990). This allows the division of the European Lower Jurassic sequence into 20 zones and 53 (Cope *et al.*, 1980) or 56 (Haq *et al.*, 1988) subzones. The zones are thought to average 1.5 m.y. in duration and the subzones about 0.5 m.y. The idea that biozone duration can be assumed equal is somewhat suspect, but it could not be objectively criticised until an independent method of dating rocks became available (Cope *et al.*, 1980).

Recent research in the American Cordillera has yielded several critical U-Pb ages, many of them integrated with ammonite biochronology at the zonal level (Palfy *et al.,* 2000). Twelve new U-Pb ages are available from the Pliensbachian and Toarcian, permitting precise estimates of zonal boundary ages though the extinction interval and to a lesser degree, the subsequent recovery. During the Late Pliensbachian, zonal durations varied between 0.4 and 1.6 Ma but their 0.9+0.3/-0.4 Ma average is statistically indistinguishable from that of the later Toarcian recovery interval (1.1+0.9/-0.7 Ma). In this case there appears to be an immediate recovery with no apparent lag period. Across this area, the correlation resolution is down to the subzonal level of timescales of perhaps 500,000 years.

Without even considering the other processes that affect the distribution and fossilisation of organisms, the periodic nature of sedimentation alone naturally impedes the preservation of

NW EUROPEAN PROVINCE		MEDITERRANEAN PROVICE	
SUBZONE	**ZONE**	**ZONE**	**SUBZONE**
Lugdunensis	AALENSIS		Fluitans
Mactra			Mactra
Pseudoradiosa	PSEUDORADIOSA	MENEGHINII	
Levesquei			
Gruneri	DISPANSUM	SPECIOSUM	Reynesi
Insigne			Speciosum
Fallaciosum	THOUARSENSE	BONARELLI	Fallaciosum
Fascigerum			
Thouarsense			Mediterraneum
Bingmanni			
Vitiosa	VARIABILIS	GRADTA	Alticarinatus
Illustris			Gemma
Variabilis			
Bifrons	BIFRONS		Bifrons
Sublevisoni			Sublevisoni
Falciferum	SERPENTINUM	LEVISONI	Falciferum?
Elegantulum			Levisoni
Semicelatum	TENUICOSTATUM	POLYMORPHUM	Semicelatum
Paltus			Mirabile

Figure 10. Lower Jurassic (Toarcian) ammonite zonation scheme proposed by Elmi et al., (1997).

fossil ranges that exhibit widespread synchronous first and last appearances. Given the probability that many stratigraphic sections do not possess entire species ranges, the assumption that first and last appearances do record evolution and extinction events can seriously compromise stratigraphic conclusions (Mann & Lane, 1995).

The Toarcian zonation has recently undergone a review by Elmi *et al.*, (1997) who propose a zonal scheme for north-west Europe that is correlated with the Mediterranean faunas. This scheme is illustrated in Figure 10, which highlights the major differences. This study, however, will use a UK ammonites zonation scheme to avoid any confusion with the new scheme of Elmi *et al.*, (1997) being noted and available for comparison. Detailed descriptions of the sections sampled in this study are given in the next section, the zonal scheme employed is given in Figure 11 along with the sampled intervals.

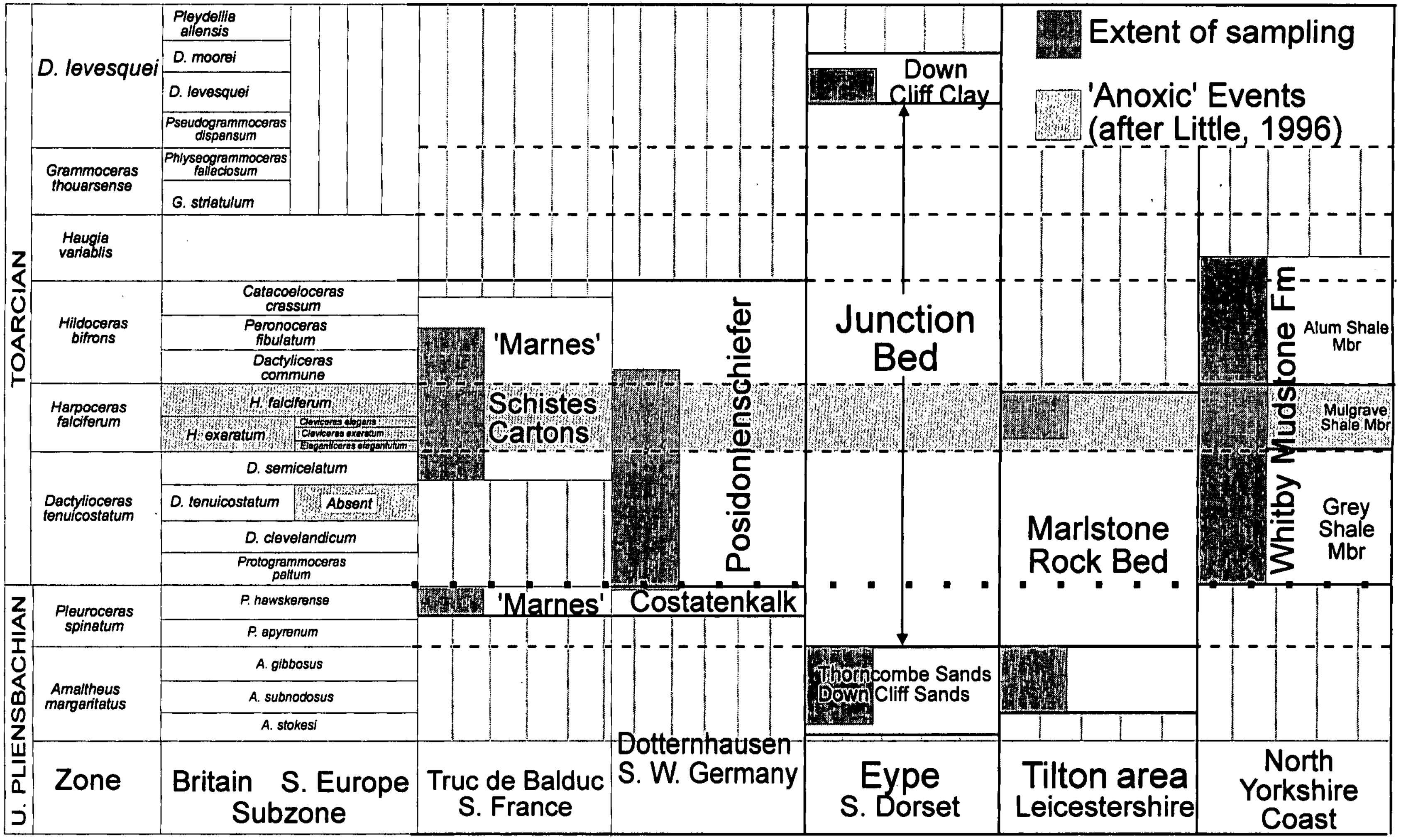


Figure 11. Stratigraphic details of sampled intervals. U.K. Ammonite Zonation after Cope et al (1980). European Zones after Riegraf (1985).

2.2.3 Main sampling localities

2.2.3.1 South Dorset Coast

The Dorset coast provides a transect of the westerly part of a broad depositional basin, the Wessex Basin, in which subsidence proceeded steadily throughout the Jurassic. Along the south Dorset coast, beds of Pliensbachian and Toarcian age are well exposed in accessible cliff sections, recently re-measured and described by Hesselbo and Jenkins (1995). In Watton Cliff, to the east of Eypesmouth, the Upper Pliensbachian to Upper Toarcian was sampled, covering a range of facies types and environments of deposition.

The Down Cliff Sands consist of up to 27m of silts and fine sands with thin lenticles of hard calcareous sandstone. Succeeding the Down Cliff Sands are 23m of the yellow-weathering Thorncombe Sands capped by the Marlstone Rock Bed which, at Watton Cliff, is welded to the bottom of overlying Junction Bed, in which it is usually included for convenience (Callomon & Cope, 1997), condensing six ammonite Zones (*spinatum* to *levesquei* Zones) into around 1m of micritic limestone, spanning the Pliensbachian - Toarcian boundary. The Upper Toarcian is then represented by the 21m of silty clays of the Down Cliff Clay, the lowest part of which is thought to represent the *levesequei* Subzone of the *levesquei* Zone (Cope *et al.*, 1980; Callomon & Cope, 1997). Samples were taken throughout this succession, as illustrated in Figure 12.

The foraminifera of the Dorset Coast have been studied by Barnard (1950a) who discussed the problems of nomenclature and homeomorphy among Lower Jurassic foraminifera while establishing the ranges and stratigraphical significance of the species encountered in the succession.

Fig. 12

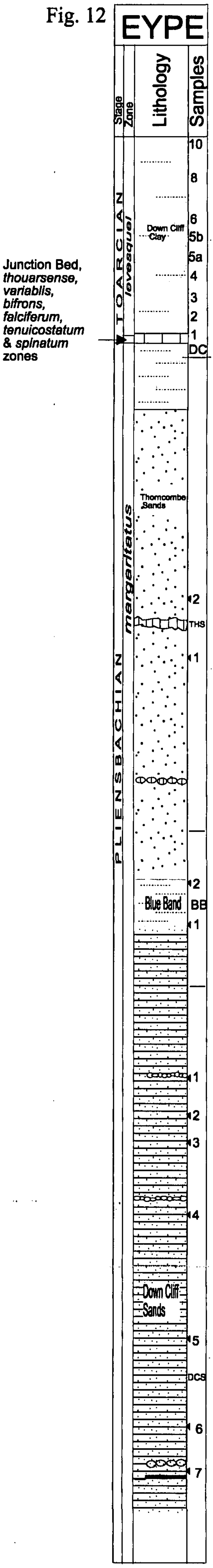


Fig. 13a

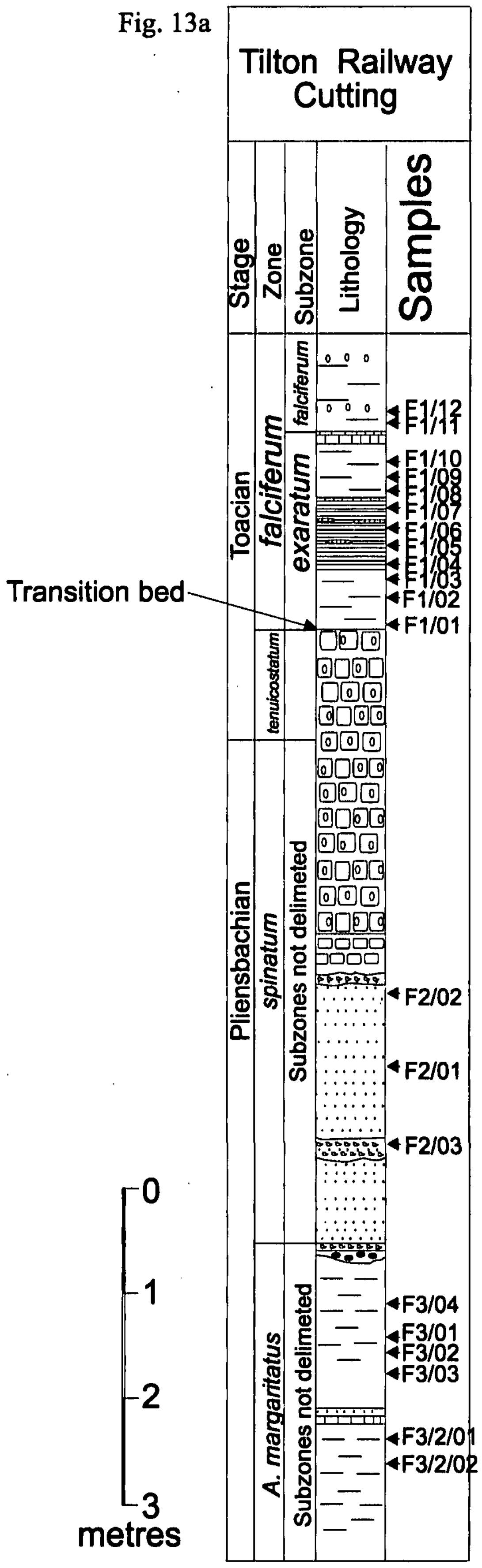


Fig. 13b

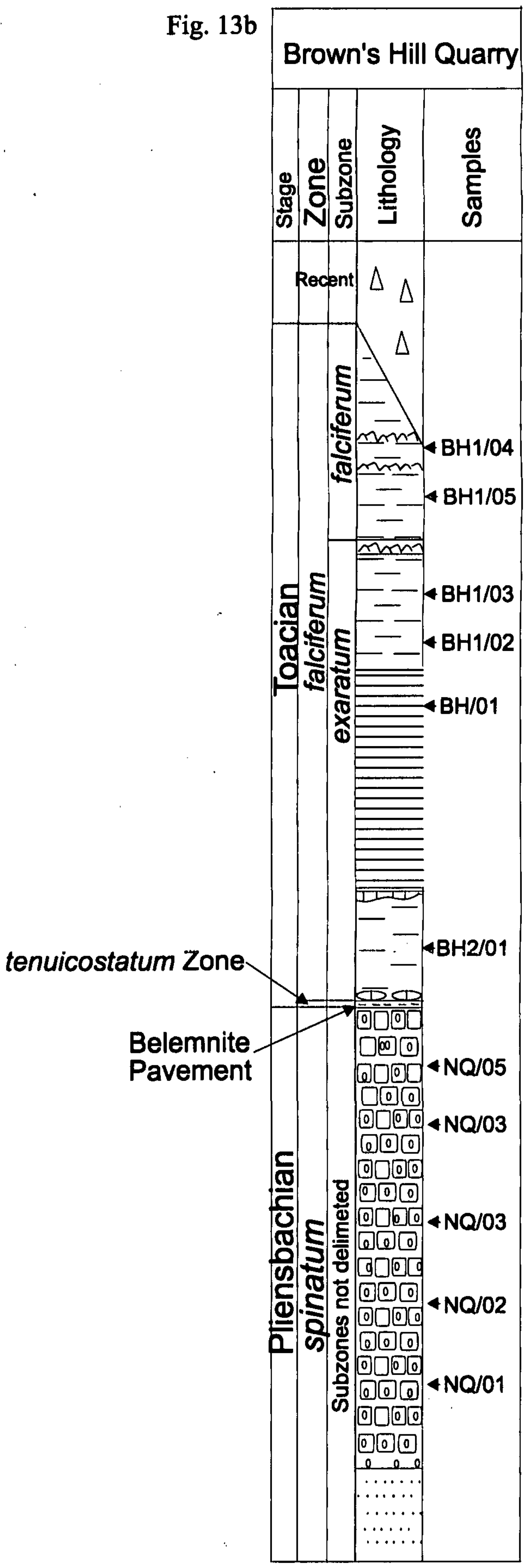


Figure 12. Graphic log of the Lower Jurassic succession at Eype, south Dorset Coast. SEction modified from Hesselbo & Jenkyns (1995).

Figure 13. Biostratigraphy of the Leicestershire sections showing locations of samples. 13a. Graphic log of the Tilton Railway section. Section measured by the author, biostratigraphy and lithostratigraphy after Cope et al. 1980). 13b. Graphic log of the section at Brown's Hill Quarry. Section measured by author, bio- and lithostratigraphy after Cope et al. 1980).

Legend

- ▭ Limestone
- ⬭ Nodular Limestone
- ▤ Organic rich mudstone
- ▭ Shale / Mudstone
- ▭ Siltstone
- ▭ Sandstone
- ▭ Ironstone (Fe-oolitic)
- ∘ ∘ ∘ Ooliths
- ⬭⬭⬭ concretions
- 〰 Shelly seams
- ⌒ ⌒ ⌒ Brachiopods
- ● ● ● Pebbles

2.2.3.2 Leicestershire

The London Platform was thought to have been an area of stable high relief during the Early Jurassic with surrounding basin margin settings. To the north of the London Platform, in exposures in Leicestershire, marginal sediments recording the extent of black shale, *falciferum* Zone, deposition can be found in disused quarries and railway cuttings.

Hallam (1955) described the section at Tilton Railway Cutting illustrated in Figure 13. The lowest part of the succession exposes 3m of Upper Pliensbachian silts and clays and the characteristic development of oolitic ironstones of the Marlstone Rock Bed. The base of the Marlstone at Tilton is a non-sequence which represents the whole of the *gibbosus* Subzone, above which the Marlstone constitutes two lithological units: 3m of calcareous and ferruginious sandstones (Sandstone Member) overlain by 2.5m of the Ironstone Member, which is a very oolitic limestone. Howarth (1980) showed that the base of the Toarcian occurs within the Ironstone member, rather than at the 'Transition Bed' level.

The Lower Toarcian is represented by 4m of mudstones and clays and lies within the *falciferum* Zone (*exaratum* and *falciferum* Subzones). A series of samples were taken from the mudstones, clays and shales above and below the Marlstone Rock Bed. The finely laminated or 'Paper' shales in the *tenuicostatum* Zone are analogous to, and roughly coeval with, the *Posidonienschiefer* of S. W. Germany.

North of Melton Mowbray, the Holwell SSSI consists of two disused quarries that are now managed as part of a biological and geological reserve. The section at Brown's Hill Quarry exposes nearly 6m of Lower Toarcian clays, mudstones, the Sandstone and Ironstone Members. It seems likely that the lowest Zone of the Toarcian is represented by the 'belemnite pavement' where organic-rich paper shales of the *falciferum* Zone are separated from the underlying Marlstone Rock Bed by a thin bed rich in fish debris resting on the pavement. Evidence for condensation comes from the high concentration of pelagic skeletal material and the extremely reduced thickness of the sediments compared to the basinal setting of Port Mulgrave in the Cleveland Basin (Wignall & Hallam, 1991).

A series of samples (Figure 13) were taken from the mudstones and clays, the higher members of which are reported to contain a high diversity micro-fauna, yielding ostracods, foraminifera, gastropods, bivalves, holothurians, ophiuroids, crinoids and fish remains (Clements, 1989; R. Clements, *pers comm.*, 1997).

Eight samples were also taken from the Sandstone and Ironstone Members to be used for thin-section analysis. These sections may help to prove the presence or absence of a foraminiferal fauna across the boundary. Lord (1974) reported poorly preserved ostracods from the Sandstone Member of the *spinatum* Zone, Tilton, while Copestake & Johnson (1989) report that foraminifera were present in the Marlstone Rock Bed of Robin's Wood Hill Quarry, Gloucester. Species included *Frondicularia terquemi* ssp. B, a marker for the latest *margaritatus* to late *tenuicostatum* Zone interval in north west Europe (Copestake and Johnson, 1989).

2.2.3.3 North Yorkshire Coast

The Cleveland Basin lay at the western margin of the main North Sea Basin. A thick Jurassic sequence accumulated which is exposed along the North Yorkshire coast. The sections studied consist of 110m of marine sediments of late Pliensbachian *margaritatus* Zone to mid-Toarcian *bifrons* Zone age, illustrated in Figure 14. The lithologies vary from mixed siliciclastic and iron-rich oolitic carbonate rocks of the Pliensbachian to finer-grained organic-poor and organic-rich shales of the Toarcian. The Whitby Mudstone Formation consists of predominantly silty, slightly to very fissile mudrocks. Vertical changes in fissility, silt content and in the abundance and nature of concretionary bands

Fig. 14a

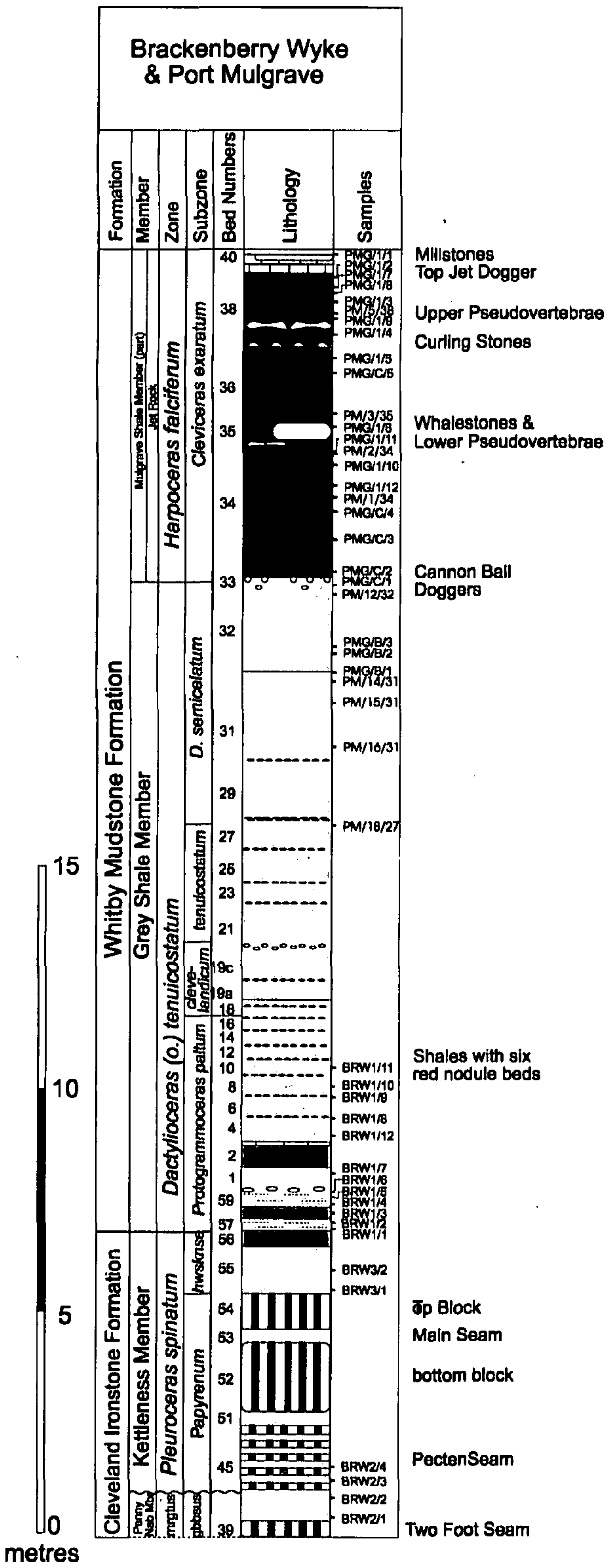


Fig. 14b

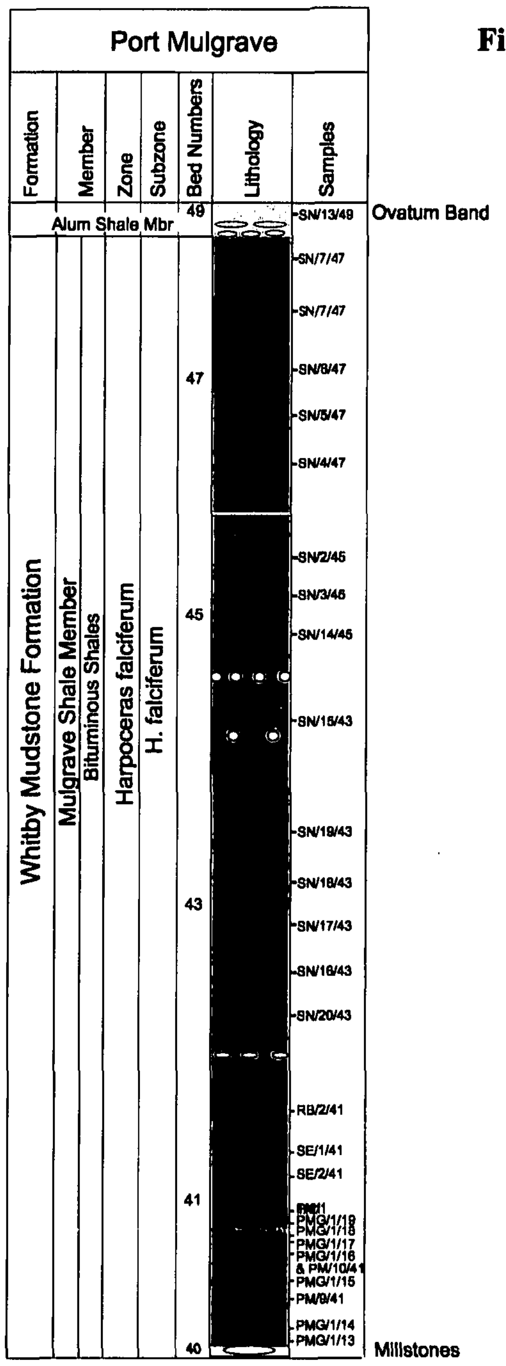


Fig. 14c

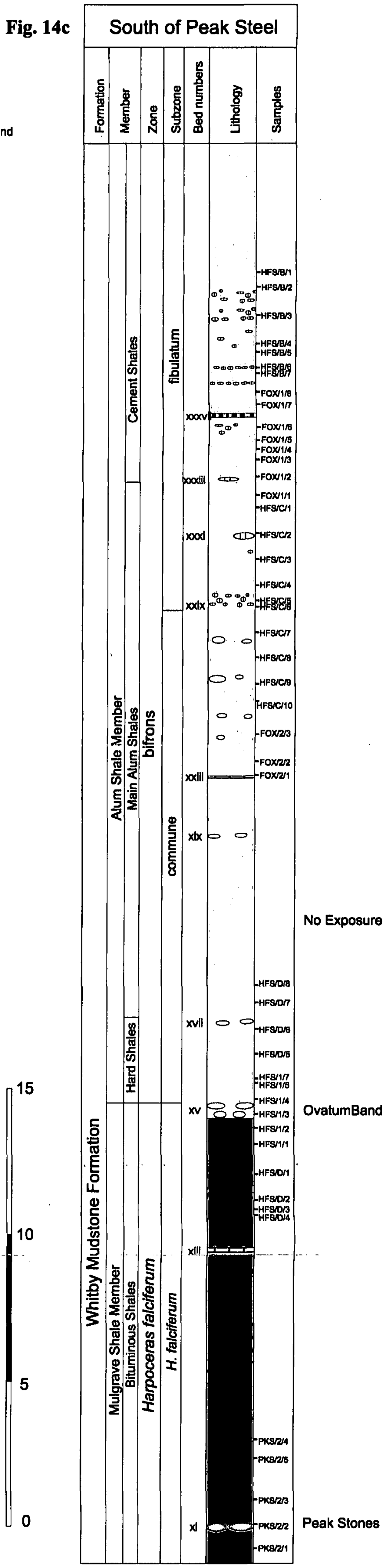


Figure 14. Graphic logs of the North Yorkshire Coast sections showing locations of samples.
14a - Brackenberry Wyke and Port Mulgrave log after Hesselbo & Jenykns (1995). 14b Port Mulgrave log after Rawson & Wright (1995). 14c. South of Peak. Log after Rawson & Wright (1995), section remeasured by author.

have led to a long-established informal division which was incorporated into a sequence of five members by Rawson & Wright (1995).

The Grey Shale Member consists of pale to medium grey silty shales with laterally consistent bands of grey- and red-weathering calcareous and sideritic nodules. The next member, the Mulgrave Shale, was proposed by Rawson and Wright (1992) as a replacement for the 'Jet Rock Member' of Powell (1984) to avoid confusion with the Jet Rock *s.s* - the lowest of three long-established informal subdivisions of the Mulgrave Shale Member, the others being the Bituminous Shales and the Ovatum Band.

The Mulgrave Shale Member differs from underlying and overlying units in being moderately to finely laminated, often weathering into a 'paper shale'. It is a medium to dark grey, richly pyritic and bituminous black shale facies, representing the anoxic phase developed during the maximum early Toarcian sea level rise and is the local equivalent of the German Posidonienschiefer. There is a rich and varied belemnite and ammonite fauna, but the benthic fauna is a very restricted, high stress assemblage showing evidence of oxygen depletion in the bottom waters (Morris, 1979).

The Jet Rock *s.s.* represents peak anoxic conditions (Pye and Krinsley, 1986). It consists of very finely laminated shales with regular bands of calcareous concretions. The overlying Bituminous Shales are less finely laminated and concretionary bands are sparse although the distinctive Ovatum Band is a 25cm thick double row of large, often red-weathering, concretions.

The Yorkshire and Dorset coasts provide the best exposures of the Lower Jurassic in the British Isles but the foraminifera of the former have not received much attention. The work of Tate and Blake (1876, pp. 232-233) provides some evidence of the presence of microfauna although it is very restricted. They found no foraminifera in the *spinatum* Zone and only one species (*Dentalina communis*) in the *margaritatus* Zone. Lord (1974) reports finding a few well-preserved benthic foraminifera 6m below the top of the *margaritatus* Zone.

A set of 30 samples from the Whitby Mudstone and Cleveland Ironstone Formations has been provided by C. Little (Figure 14) with the aim of correlating the microfaunal data with the macrofaunal data (Little, 1996).

Samples were collected from accessible sections from the base of the Toarcian at Brackenberry Wyke, through to the Alum Shales in the Upper Toarcian (Figure 14).

2.2.3.4 South Central France

The Lower Toarcian Jet Rock and Bituminous Shales of Yorkshire and their equivalents in the North Sea, France (Schistes Cartons), Germany and Switzerland (Posidonienschiefer) are all indicative of periods of deposition of organic-rich shales during the *falciferum* Zone (Jenkyns, 1988). The bituminous shales of the Truc de Balduc represent the deepest facies of a cycle of sedimentation when the basin reached its maximum depth in the Early Toarcian at the peak of Early Jurassic transgression. The facies and fauna of the Lower Toarcian of Southern France also show close relationships to southwest Germany and to the Whitby area (Riegraf, 1982). In the area of the Truc de Balduc, S. France (Figure 16) the *falciferum* Zone is present and the *bifrons* Zone is unusually thick compared to the Yorkshire sections. The Bituminous Shales are well developed and contain a diverse microfauna. In their lowest part they contain very small foraminifera, echinoderms, gastropods and bivalves (Riegraf, 1982, 1985). Several limestone layers in the bituminous facies can be correlated over very long distances in Europe. One layer, named "Untere Bank" occurs in the same stratigraphic level and facies in S. W. Germany ("Untere Stein") and has an equivalent of the same age in Whitby (the Whalestone of Howarth, 1962).

Fig. 15

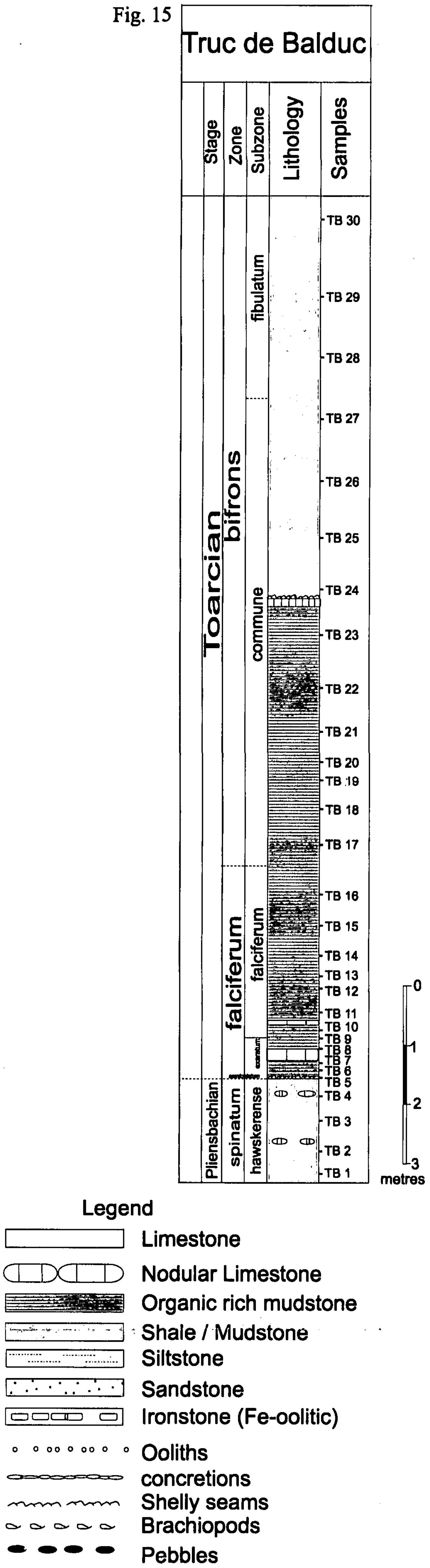


Fig. 16

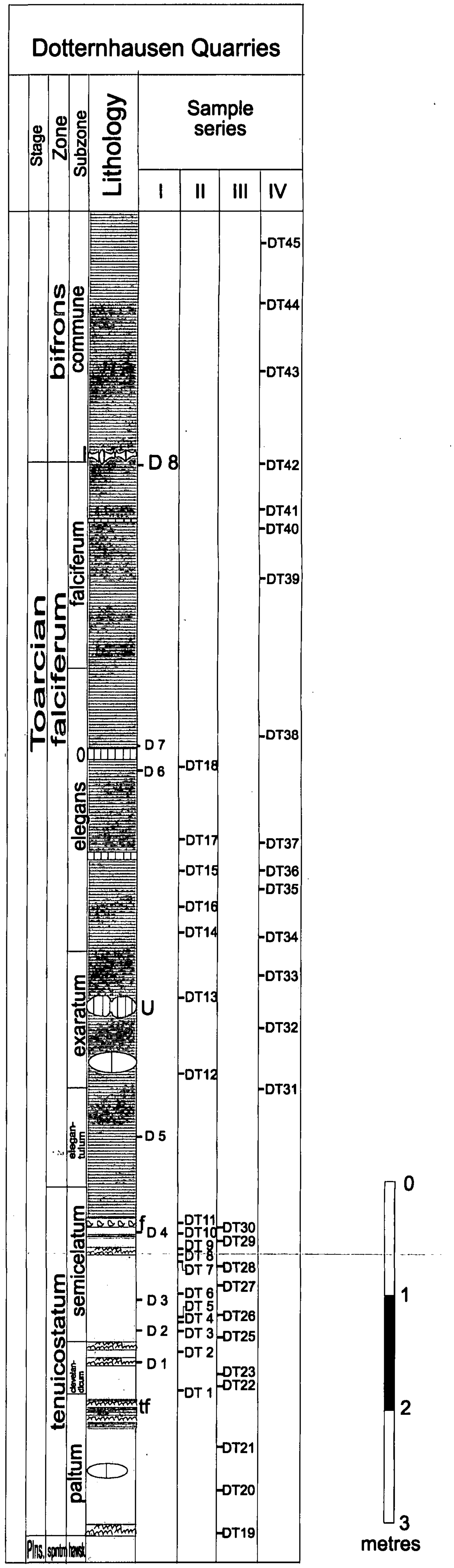


Figure 15. Graphic log of the Truc de Balduc section, southern France with sample locations. Bio- and lithostraigraphy after Riegraf, (1995).

Figure 16. Graphic log of the Dotternhausen Quarries sections with sample locations. Bio- and lithostratigraphy after Riegraf, (1995).

2.2.3.5 South-west Germany

The Pliensbachian - Toarcian sections in Baden-Württemburg, south-west Germany are thinner and more calcareous than those on the North Yorkshire coast, although they share similar faunal and facies trends (Little, 1996). The main extinction event occurs in the *semicelatum* Subzone coincident with the most organic-rich part of the Posidonienschiefer, equivalent to the Jet Rock Member. The Posidonienschiefer is well-developed in a series of quarries near Dotternhausen (Figure 16), south-west Germany and have yielded a rich micro-fauna including foraminifera and ostracods (Riegraf, 1985). For this study, a set of eight pilot samples, from mid-*tenuicostatum* to the base of the *bifrons* Zone has been provided by Dr Manfred Jäger, Quarry Museum Manager of the Rohrbach Cement Works. This initial set of samples was later supplemented by a more extensive sampling programme during a visit to the quarry. The quarries consisted of three main areas of excavation, illustrated on Figure 16. Section III reached the lowest level, extending from the base of the Toarcian up to the 'fliens' level. The disused section II extended 1.5m below the 'fliens' level and up to the distinctive Oberer Stein limestone. Section IV, in the working part of the quarry allowed access to the higher levels up to the *commune* Subzone. A comparison between samples taken from the same level but at different parts of the quarry may reveal some indication of the lateral persistence of foraminiferal faunas.

2.2.4 Additional localities

2.2.4.1 East Quantoxhead

The Lower Jurassic in Northern Europe is dominated by relatively thick, complete sequences of argillaceous facies which are extensively developed on the west Somerset coast. This marine sedimentary formation comprises a sequence of alternating small scale limestone and shale rhythms, often containing finely laminated (bituminous) shales.

Fig. 17.

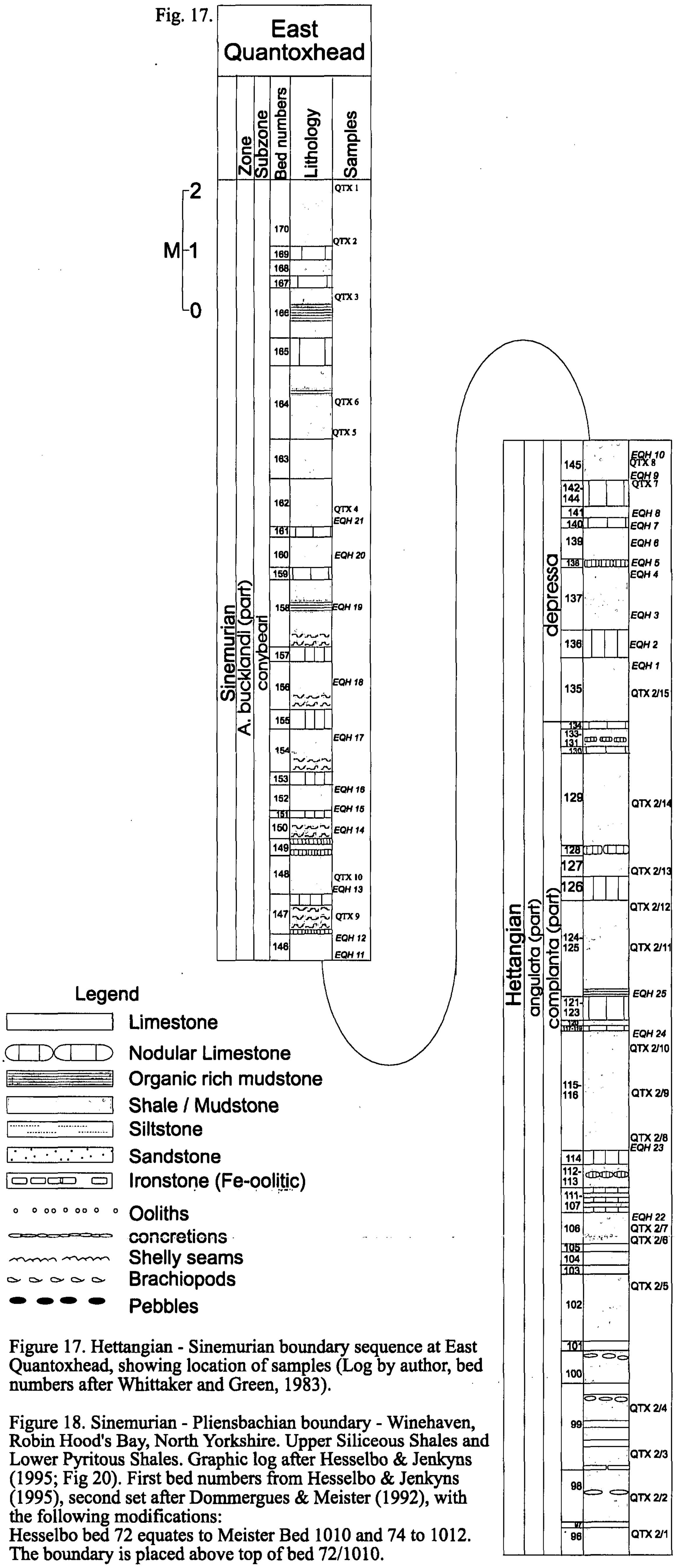


Fig. 18

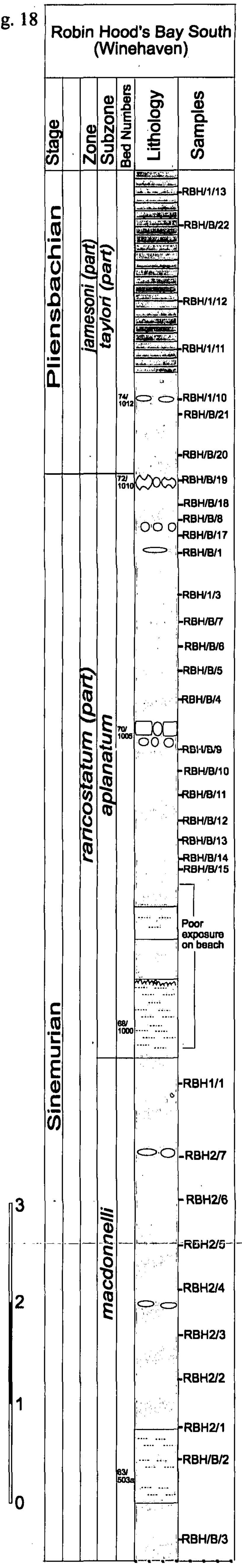


Figure 17. Hettangian - Sinemurian boundary sequence at East Quantoxhead, showing location of samples (Log by author, bed numbers after Whittaker and Green, 1983).

Figure 18. Sinemurian - Pliensbachian boundary - Winehaven, Robin Hood's Bay, North Yorkshire. Upper Siliceous Shales and Lower Pyritous Shales. Graphic log after Hesselbo & Jenkyns (1995; Fig 20). First bed numbers from Hesselbo & Jenkyns (1995), second set after Dommergues & Meister (1992), with the following modifications:
Hesselbo bed 72 equates to Meister Bed 1010 and 74 to 1012.
The boundary is placed above top of bed 72/1010.

This study has involved the preliminary investigation of the potential of the section as a Global Stratotype Section and Point (GSSP) for the base of the Sinemurian stage (Hylton, 1998, 1999).

The stratigraphy of the Lower Jurassic of the north Somerset coast was described by Palmer (1972) with a more recent redescription made by Whittaker and Green (1983) who proposed the scheme for the Hettangian - Sinemurian boundary sequence in Figure 17.

Copestake (1975) described Hettangian-Sinemurian faunas of the Mochras Borehole in North Wales, from the most complete Lower Jurassic sequence in the United Kingdom. Although there is no published research on the foraminifera of the Hettangian- Sinemurian of the north Somerset coast, Copestake and Johnson (1989) list the ranges of seven species known from the Hettangian of St. Audries Slip and Watchet compiled from unpublished data.

A total of fifty samples of shale and mudstone were taken at the locations shown in Figure 17 with an emphasis placed on the boundary shale. Samples labelled EQH were provided by Dr. K. N. Page and those labelled QTX were collected by the author. The former two series of samples were taken from the cliff exposures while samples in the QTX/2 series were taken from the extensive wave cut platforms. Samples from the limestone beds were not included in this study.

2.2.4.2 Robin Hood's Bay

A major outcrop of the Lower Jurassic can be found in the Robin Hood's Bay structural dome, where a complete sequence of zones down to the Sinemurian *semicostatum* Zone can be studied. The Redcar Mudstone Formation is better exposed in Robin Hood's Bay than anywhere else on the Yorkshire coast but despite the excellent exposure, no detailed section had been published since the study by Tate & Blake (1876) until Hesselbo &

Jenykns (1995) produced a log for the whole section.

The section spanning the Sinemurian - Pliensbachian transition is illustrated in Figure 18 and comprises the upper part of the Siliceous Shales and the lower part of the Pyritous shales. The Siliceous shales consist of fully marine silty shales with thin more harder siltstones and fine sandstones that become thicker and more frequent upward. There is a rapid passage into the Pyritous Shales, the facies change marking the basal Pliensbachian sea level rise. The Pyritous shales consist mainly of a sequence of dark, almost black, shales with bands of sideritic concretions.

This section is currently under investigation as a possible Global Stratotype Section and Point for the base of the Pliensbachian as it contains an unrivalled biostratigraphic sequence of ammonites around the Sinemurian - Pliensbachian boundary (Dommergues & Meister, 1992).

2.3 Reconnaissance methods

2.3.1 Sample preparation

Some of each sample was retained unprocessed as a safeguard against contamination during processing and the possible need for a sample check. Approximately 150 grams of material was processed using the techniques described below. The sediments collected from the Pliensbachian - Toarcian successions varied greatly in their composition and consequently required novel methods of disaggregation. However, processing for all the samples began with the application of the widely used solvent method (Bolli, 1952; Brasier, 1980) which is particularly effective on indurated argillaceous rocks.

The samples were manually broken down into fragments of around 5-10mm in diameter, dried at 60°C in an oven for 12 hours and then soaked in white spirit for a further 8 hours.

The white spirit was then decanted off and the sample soaked in distilled water for around 8 hours. While this method was quite successful on clay rich samples it was found that replacing the distilled water with a hot solution of washing soda (Na_2CO_3) resulted in more efficient disaggregation.

While many of the samples were quite argillaceous, the more indurated samples did not disaggregate using this method only. If breakdown was not complete at this point the sample was dried again in the oven before using a second technique described by Bolli (1952) and Johnson (1975). This involved boiling the sample in a solution of washing soda (Na_2CO_3) for one hour after which time some of the fine clays were in suspension. The suspension was poured through a 74 μm sieve so that the finer material was washed away, The residue was then reboiled in washing soda solution until there was no further noticeable breakdown.

The above techniques were not very effective on the more organic-rich or bituminous sediments that required treatment with different methods. In these cases, the samples were dry heated and soaked in a 10% solution of hydrogen peroxide (in a fume cupboard). This generates a large amount of heat and good disaggregation is normally obtained.

Samples with a higher organic or bituminous content have also been treated by soaking in a 15% NaClO, domestic bleach, solution for around one week. This technique works well with indurated carbonaceous shales, mudstones and clays, although disaggregation is slow compared to other methods.

A further technique involved the use of sodium tetraphenylborate (NaTBP) and sodium chloride, as described by Martin-Hanken (1979) and modified by Muller (1990). This is a very effective and rapid technique on a wide range of lithologies and the method is based upon the expansion occurring when interlayer potassium in mica is exchanged with hydrated sodium ions. Unfortunately the high cost of NaTBP prohibited the application of this technique to any more than a few test samples during this study. Table 3 summarises the effectiveness of the techniques used on the typical types of lithologies from this study. It shows that each method has a limited range of application but with some initial consideration of the lithology of the sample, a suitable technique can be chosen.

Technique / Lithology	Basic Solvent Method	Solvent with hot Na_2CO_3	Boiling in Na_2CO_3	Hydrogen Peroxide	NaOH	NaTBP
High % Clay	☺	☺	x	x	x	x
High % Mud	☺	☺	☺	x	x	x
Shale	😐	😐	☺	x	x	x
Bituminous Shale	☹	☹	☹	😐	😐	☺
Indurated (Siliceous) shale	☹	☹	x	x	x	x

Key: 😐 Moderate success; ☹ No effect; ☺ Very Successful; **x** - not tried.

Table 3. Summary of the effectiveness of disaggregation techniques on a range of lithologies encountered in this study

The residues from all the techniques were washed with water through a 74µm sieve. During this washing process, and when filtering suspended material during other methods, it was found that the addition of soap, usually household 'washing-up liquid', greatly speeded up the separation of clays from the residues while actually aiding the process of disaggregation (after Howe, 1941). The residues were finally dried in an oven at 60°C, weighed and stored in labelled plastic flip-top tubes.

2.3.2 Picking rationale

An examination of the micropalaeontological literature reveals little consensus of what constitutes a valid methodology for picking foraminifera from residues in order to gain a representative measure of the fauna in that sample. There are several issues involved: initial considerations of the sieve size used; whether to split the sample into aliquots and finally how many individuals to pick per sample or aliquot. Copestake (1978) sieved each sample to 500µm, 250µm and 150µm retaining 0.5g of the 63µm material. The numbers of individuals in all samples were counted and recalculated to a theoretical number expected to occur in 0.5g of 63µm and 1g of 150µm material. Conversely Nini *et al.*, (1995) examined 6g of material over 63µm and picked 300 individuals per sample. Similarly, Bartolini *et al.*, (1992) examined 1g of residue from each sample and where possible picked between 200 and 400 individuals. Nagy (1985a) chose to pick foraminifera from the fraction >125µm after sieving the residue though 63, 125, 250 and 500µm sieves.

The 74µm limit was chosen for this study, over coarser fractions, as it provides a better spectrum of potential indicator species and produces larger assemblages (over 300 specimens) which are likely to provide a more reliable statistical base (Schröder *et al.*, 1987). This lower limit also provides the best possible ratio of residue to fossils while eliminating all the clay and silt. Sieves with larger mesh sizes allow a significant loss of specimens, including environmentally useful species and may create artificial 'barren intervals' in sequences dominated by small-sized species. The number of specimens examined per sample varies from researcher to researcher, depending upon the degree of precision required for a particular study. The absolute number of specimens generally varies between 200 and 1,000 per sample. However, most workers usually count approximately 300 specimens. Phleger (1960) who, based upon experience and on an equation derived by Dryden (1931) for counting heavy mineral grains, suggested that 300 specimens provided sufficient accuracy for most quantitative examinations.

Brouwer (1969) found that Lower Jurassic foraminiferal faunas were rather monotonous in composition, because of the predominance of lagenid species. These dominant species can be considered the main components of the assemblages. In the passage from one environment into another, one or more of the main components (i.e., those components constituting 5% or more of the total benthonic fauna) are usually replaced by others, thus

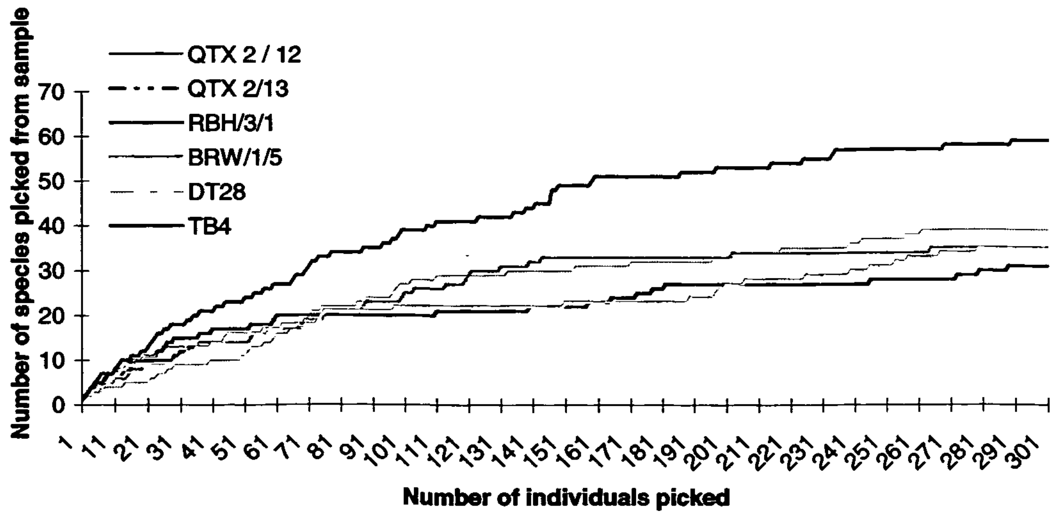


Figure 19. Graph of new species appearance against cumulative total.

leading to other combinations. Patterson & Fishbein (1989) recommend that counts of 500-1000 are required to accurately determine species abundance percentages of 5% and counts of 300 for species comprising 10% while Buzas (1990) suggests that a count of greater than 300 individuals is sufficient for a single sediment sample. In order to test the hypothesis that 301 individuals from >74μm fraction produce a representative fauna, the appearances of new species were plotted against the cumulative number of individuals picked. Figure 19 demonstrates, for a range of samples picked during this study, that there would be no appreciable gain in the retrieval of new species by continuing to pick over 301 individuals per sample.

The residues were examined on a gridded tray under a binocular microscope and greater than 300 individuals from each sample were picked where possible to obtain a representative assemblage of the species present (Dennison and Hay, 1967).

2.3.3 Examination and identification

A Scanning Electron Microscope (SEM) was used to inspect the microfossils at higher magnifications. A well preserved individual of each species was selected and mounted on a carbon tab covered plain stub. The stubs were then coated with gold and examined using a JEOL 5100 SEM at 25kv. A Semafore Digital Camera system was used to capture a bitmap image of the specimen that was then stored on a hard copy printout and also on a ZIP Disk. Proprietary software was used to edit the images and allow them to be collated into plates.

Chapter 3 Taxonomy

3.1 Background to the classification

The problems encountered during the systematic treatment of Lower Jurassic foraminifera are well documented (Norling, 1972; Johnson, 1975; Copestake, 1978; Haynes, 1990). A major difficulty is the great degree of variation exhibited by many species, illustrated by the Nodosariacea in particular. Macfadyen (1941) solved several taxonomic problems while Barnard (1950a, 1956, 1957, 1960) dealt with the problem of intraspecific variation in Jurassic foraminifera. Adams (1957) also examined the variation within Toarcian foraminifera. The foraminifera of the Mochras borehole were studied by Johnson (1975) and Copestake (1978) and a great deal of work is contained within these two theses including extensive reference lists, modified classification schemes and discussion of plexus studies. Unfortunately this work remains largely unpublished with 75 index species described in Copestake & Johnson (1989).

Taxonomic confusion within Lower Jurassic foraminifera results partly from the great variation of species and partly from the poor quality of Terquem's figures and descriptions (Copestake and Johnson, 1989). The large number of species erected since the early works in the 18th Century becomes apparent when examining the literature concerning Lower Jurassic foraminifera from the United Kingdom and Europe. Section 3.1.1 describes the use of plexus groupings to cover recognisable subspecies that re-occur stratigraphically. Many species are obviously synonymous, for instance the characteristic *Lingulina tenera* Bornemann plexus of Copestake and Johnson (1989) is variously known as *Geinitzina tenera* (Bornemann) by Nørvang (1957), later transferred to *Paralingulina tenera* by Loeblich and Tappan (1988a). The ornamented *Frondicularia* create their own taxonomic problems which are well illustrated by *Frondicularia terquemi sulcata* Bornemann. This subspecies is highly variable in terms of rib number, rib orientation and test width and many 'species' names are available for the various forms. Many authors have attempted to make sense of the variation and evolution, but without consensus (Barnard, 1957; Nørvang, 1957; Norling, 1968; Ruget, 1967, 1988). Barnard (1957) proposed the *Frondicularia sulcata* plexus and described its evolution. These plexus forms have stratigraphic significance (Copestake and Johnson, 1989) but the assessment and correlation of these forms outside Britain is not possible as other workers (e.g., Ruget, 1967, 1988; Riegraf, 1985) have not recognised Barnard's forms. The same problem arises with many of the other plexus groups of the Lower Jurassic; the *Lingulina tenera* Bornemann plexus, *Lenticulina muensteri* (Roemer) plexus, *Lenticulina varians* (Bornemann) plexus, *Marginulina prima* (d'Orbigny) and the *Pseudonodosaria vulgata* (Bornemann) plexus are all associated with the explosive burst of the Nodosariacea during this part of the Jurassic.

The main objective of the classification scheme employed in this study is therefore to attempt to describe the species and subspecies recovered from the European sections within a consistent taxonomy The data collected may then help in defining the geographic and stratigraphic distribution of plexus forms recovered while correlating these forms with those described by continental European workers (e.g., Nørvang, 1957; Norling; 1972; Brouwer, 1969; Riegraf, 1985).

3.1.1 Variation within species

As noted above, within the generally variable species of the Nodosariidae, high intraspecific variation resulted in the production of a wide range of morphotypes. The work of Johnson (1975) and Copestake (1978) showed that many of these were variants, which occurred throughout the species range, connected by intermediates to the original species characteristics. Though such variants were found to have little stratigraphic significance, horizons at which they were common were thought to be reflecting particular environmental conditions. Other morphotypes were found to be easily separable morphologically from the central form of the species, through most of their range. Where such forms also had a restricted range, they could be regarded as a subspecies. These could be either a chrono-subspecies (*sensu* Drooger, 1954) or geographical subspecies. It has been suggested that two geographical subspecies can not exist at the same locality and that two chronological subspecies can not exist at the same horizon (Boltovskoy, 1954; Sylvester-Bradley, 1951). Theoretically this is true, as two subspecies of a single species must remain isolated in order to maintain their genetic and morphological distinctiveness. However, as Copestake (1978) points out, a palaeontologist's sample, though taken from a single horizon, is probably a thanatocoenosis composed of the remnants of more than one population. For example, the component fossils may have been transported from an area which included the ranges of more than one geographical subspecies. This need not have been a large area, since these subspecies may have occupied slightly different ecological niches within a small distance. In any case, the recognition of geographic subspecies is extremely difficult, as contemporaneity is almost impossible to establish (Nørvang, 1957; Tappan, 1977). The concept of the subspecies used here is that of chrono-subspecies; evolutionary units prevented from interbreeding by differences in time.

Species which contain a number of recognisable subspecies as well as many variants are well known from the Lower Jurassic, e.g., *Lingulina tenera*, *Frondicularia terquemi*, *Marginulina prima*. These species show progressive evolution through the Lower Jurassic. In view of the wide range of morphotypes and the high degree of variation in these species, the term species plexus has been utilised for such cases (see Barnard, 1950a, 1956, 1957, 1960; Copestake, 1978; Copestake & Johnson, 1989). Copestake (1978) defined the plexus *as 'a single, variable, polytypic species which is evolving and has thus produced distinct* *subspecies, in addition to many variants, during the course of its development'.* The abbreviation plex. has been proposed for the plexus and used as for example, in *Lingulina tenera* Bornemann plex. (Copestake & Johnson, 1989; Copestake, 1978). Individual members of this plexus are then referred to, using standard tripartite nomenclature, as for example *Lingulina tenera* plex. *pupa* or *Lingulina tenera* plex. form C.

3.1.2 Notes on the classification

The generic and suprageneric classification used is, for the most part, that of Loeblich and Tappan (1988a). However, where the present scheme differs from this, a definition will follow the taxonomic unit and a short comment will discuss the differences and, if possible, give references to other classifications and usage. To illustrate one such difference, Tappan and Loeblich (1988a) recognise genera on the basis of test architecture and coiling mode, aperture form and accessory structures and internal structures. However, previous taxonomic studies on Lower Jurassic foraminifera have stressed that chamber arrangement is the fundamental biocharacter and is of familial and subfamilial importance in the Nodosariidae (Copestake, 1978). Apertural form and cross-sectional test shape are then considered to be of equal and generic significance. External features such as ornament and sutural characters are of specific and subspecific value. This approach is taken in the present study as it emphasises the changes that occur during this part of the Jurassic.

While a full monographic treatment of the fauna is beyond the scope of this study, following each genus, a remarks section will describe the author's concept of that particular genus and will include any variation of the taxon. The major deviations occur within the Lagenina where the diagnoses given do not make a clear distinction between the Nodosariidae and Vaginulinidae because both can include arcuate to uncoiled genera. The subfamily Marginulininae cannot be distinguished from the Vaginulininae on the diagnoses given by Loeblich and Tappan (1988a). Following the scheme of Copestake (1978), the Marginulininae is subsumed into the subfamily Lenticulininae.

Reference lists will be limited to the original designation with subsequent references only included to show major generic shifts; additional references may be included if necessary or where a superior description or illustration is present and which closely resemble the present diagnosis of the taxon. A recent designation will also be included where possible.

Specific descriptions will comprise a brief diagnosis in the case of a well-known species which is well established in the literature. A full description will only be included where the author's concept of the species is significantly different, or in the case of poorly described or new taxa. The total stratigraphic range will be given using additional data from the literature. The regional occurrences and ranges are available in Tables 4 and 5 of Chapter 4. Additional information may be included in a remarks section while the material studied will be quantified for each species.

All taxa are illustrated by SEM digital photomicrographs captured using a JEOL SemAfore digital slow-scan image recording system on a JEOL JSM-5200 SEM. The taxa are presented in Plates 1-10. Some taxa are shown in transmitted light views to demonstrate chamber arrangement; this is important for the specific and generic identification of the Miliolina. These were obtained by photography using a petrographic microscope

3.2 Systematic descriptions

Order **FORAMINIFERIDA** Eichwald, 1830

Suborder **TEXTULARIINA** Delage and Hérouard, 1896

Superfamily **ASTRORHIZACEA** Brady, 1881

Family **SACCAMMINIDAE** Brady, 1884

Subfamily **SACCAMINIINAE** Brady, 1884

Genus *Lagenammina* Rhumbler, 1911

Lagenammina jurassica (Barnard)

Pl. 1, Figs 11-14.

1959 *Proteonina jurassica* Barnard, p. 134, pl. 11, figs 6-8.

1972 *Lagenammina* ex gr. *difflugiformis* (Brady); Norling, p. 40, pl. 13a.

1985 *Lagenammina jurassica* (Barnard); Riegraf, p. 92, pl. 5, figs 19, 20.

DIAGNOSIS: A species of *Lagenammina* that consists of one flask-shaped chamber with a long drawn out neck of constant diameter with the aperture forming the open end.

STRATIGRAPHICAL RANGE: This species has been recorded throughout the Lower Jurassic. Copestake (1978) gives a range of *bucklandi* Zone to uppermost Toarcian.

MATERIAL: 163 specimens.

Subfamily **THURAMMININAE** A. D. Miklukho-Maklay, 1963

Genus *Thurammina* Brady, 1879

Thurammina jurensis (Franke)

Pl. 1, Fig. 7.

1936 *Thyrammina jurensis* Franke, p. 13, pl. 1, fig. 8.

1969 *Thurammina jurensis* Franke; Brouwer, p. 24, pl. 1. fig. 23.

1985 *Thurammina jurensis* (Franke); Riegraf, p. 93, pl. 5, figs 15-18.

1989 *Thurammina jurensis* (Franke); Copestake and Johnson, p.164, pl. 6.2.1, fig. 5.

DIAGNOSIS: A small species of *Thurammina* that is identified by its small size and spiky to honeycomb surface ornamentation.

STRATIGRAPHICAL RANGE: Total range of Lower Toarcian (*bifrons* Zone) to Aalenian (*opalinum* Zone).

MATERIAL: 28 individuals.

Superfamily **AMMODISCACEA** Reuss, 1862

Family **AMMODISCIDAE** Reuss, 1862

Subfamily **AMMOVOLUMMINA** Chernykh, 1967

Genus *Ammodiscus* Reuss, 1862

Ammodiscus siliceus (Terquem)

Pl. 1, Figs 1, 4-5.

1862 *Involutina silicea* Terquem, p. 456, pl. 6, fig. 11a, b.

1863 *Ammodiscus asper* Terquem, pl. 2, fig. 1.

1969 *Ammodicus asper* (Terquem); Brouwer, p. 24, pl. 1, figs 6-9.

1969 *Ammodiscus siliceus* (Terquem); Brouwer, p. 24, pl. 1, figs 10,11.

1985 *Ammondiscus siliceus* (Terquem); Riegraf, p. 94, pl. 5, figs 21-23.

1989 *Ammodiscus siliceus* (Terquem); Copestake and Johnson, p. 164, pl. 6.2.1, fig. 1.

DIAGNOSIS: This variable species of *Ammodiscus* has a test comprising an arenaceous tube of four to eight whorls arranged in a circular or ovate planispire.

REMARKS: This study agrees with authors who consider *Ammodiscus asper* to be a synonym (Copestake and Johnson, 1989; Riegraf, 1985) where Lower Jurassic *Ammodiscus* populations contain both forms in a single variable species.

STRATIGRAPHICAL RANGE: Throughout the Lower Jurassic and into the Aalenian. Most common in the Upper Sinemurian (Copestake and Johnson, 1989).

MATERIAL: 297 specimens.

Superfamily **LITUOLACEA** de Blainville, 1827

Family **HAPLOPHRAGMOIDIDAE** Maync, 1952

Genus *Haplophragmoides* Cushman, 1910

Haplophragmoides barrowensis Tappan

Pl. 1, Fig. 17.

1951 *Haplophragmoides? barrowensis* Tappan, p. 1, pl. 1, fig. 5a-b.

1955 *Haplophragmoides barrowensis* Tappan, p. 42, pl. 11, figs 1-5.

DIAGNOSIS: A species of *Haplophragmoides* that has a compressed, planispiral, evolute test with a rounded periphery. The test wall is rough with larger grains in a groundmass of finer material. The sutures are indistinct in the earliest whorls, becoming more constricted in the later ones.

STRATIGRAPHICAL RANGE: Tappan (1955) gives occurrences in the Early Jurassic and specifically, in the Early Toarcian.

MATERIAL: 46 specimens.

Haplophragmoides kingakensis Tappan

Pl. 1, Fig. 16

1955 *Haplophragmoides kingakensis* Tappan, p. 43, pl. 10, figs 1-6.

1972 *Haplophragmoides kingakensis* Tappan; Norling, p.43, fig. 13b.

1985 *Haplophragmoides kingakensis* Tappan; Riegraf, p. 97, pl. 6, figs 3-5.

DIAGNOSIS: A species of *Haplophragmoides* that is distinguished by the increase in breadth of the chambers in the final whorl and nearly straight sutures.

REMARKS: This species of *Haplophragmoides* differs from other species by its inflated chambers and more deeply incised sutures.

STRATIGRAPHICAL RANGE: Norling (1972) gives a range of Pliensbachian - Toarcian, which was extended to *bucklandi* Zone to uppermost Toarcian by Copestake (1978).

MATERIAL: 52 specimens.

Family **LITUOLIDAE** de Blainville, 1827

Subfamily **AMMOMARGINULININAE** Podobina, 1978

Genus *Ammobaculites* Cushman 1910

Ammobaculites fontinensis (Terquem)

Pl. 1, Fig. 15

1870 *Haplophragmium fontinense* Terquem, p. 235, pl. 24, figs 29-30.

1950a *Ammobaculites fontinensis* (Terquem); Barnard, pl. 1, figs 1, 2.

1969 *Ammobaculites fontinensis* (Terquem); Brouwer, pl. 1, figs 1-3.

1985 *Ammobaculites vetusta* (Terquem and Berthelin); Riegraf, p. 97, pl. 6, figs 6-9.

1958 *Ammobaculites fontinensis* (Terquem); Riegraf, p. 97, fig. 10.

DIAGNOSIS: A species of *Ammobaculites* with an initial coiled disc-like section and a later rectilinear spire.

STRATIGRAPHICAL RANGE: *ibex* Zone? to uppermost Toarcian (Copestake, 1978).

MATERIAL: 10 specimens.

Superfamily **TROCHAMMINACEA** Schwager, 1877

Family **TROCHAMMINIDAE** Schwager, 1877

Subfamily **TROCHAMMININAE** Schwager, 1877

Genus *Trochammina* Parker and Jones, 1859

Trochammina canningensis Tappan

Pl. 1, Figs 6, 9, 10, 19.

1955 *Trochammina canningensis* Tappan, p. 49, pl. 14, figs 15-19.

1989 *Trochammina canningensis* Tappan; Copestake and Johnson, p. 166, pl. 6.2.1, figs 10-12.

DIAGNOSIS: A species of *Trochammina* with a distinctive globigeriniform test which is low to high spired with globular chambers.

STRATIGRAPHICAL RANGE: Hettangian-Kimmeridgian of northwest Europe and Alaska (Copestake and Johnson, 1989).

MATERIAL: 11 specimens.

Trochammina occulta (Bach)

Pl. 1, Figs 21, 22.

1959 *Choffatella occulta* Bach; Bach, Hegenmeyer and Neuweiler, p. 429, pl. 21, fig. 2.

1960 *Trochammina occulta* (Bach); Bizon and Bizon, p. 143.

1985 *Trochammina occulta* (Bach); Riegraf, p. 99, pl. 6, figs 25-27.

DIAGNOSIS: A species of *Trochammina* that is distinguished by its elongate conical test with an umbilicus on one side and an evolute coil on the other.

STRATIGRAPHICAL RANGE: Sinemurian to Callovian (Riegraf, 1985).

MATERIAL: 115 specimens.

Trochammina sablei Tappan

Pl. 1, Fig. 18.

1955 *Trochammina sablei* Tappan, p. 50, pl. 4, figs 6-9.

1985 *Trochammina sablei* Riegraf, p. 99, pl. 6, fig. 21.

DIAGNOSIS: A species of *Trochammina* that has a low-spired trochoid test with a rounded periphery. The chambers are inflated and rounded with slightly depressed sutures.

STRATIGRAPHICAL RANGE: *liascus* Zone to uppermost Toarcian (Copestake, 1978).

MATERIAL: 136 specimens.

Trochammina topagorukensis Tappan

Pl. 1, Fig. 8.

1955 *Trochammina topagorukensis* Tappan, p. 51, pl. 14, figs 10-11.

1977 *Trochammina topagorukensis* Tappan; Horton and Coleman,
p.7, pl. 2, figs 10-11.

1981 *Trochammina gryci* Tappan; Copestake and Johnson, p. 90, pl. 6.1.1, figs 4, 6.

1985 *Trochammina topagorukensis* Tappan; Riegraf, p. 99, pl. 6, figs 19-20, 22-24.

DIAGNOSIS: A species of *Trochammina* that is distinguished by its globular and inflated chambers with curved sutures.

REMARKS: This species is also distinguished by its small size compared to *Trochammina gryci* Tappan.

STRATIGRAPHICAL RANGE: Copestake and Johnson (1981) restrict this species to the Sinemurian, while Riegraf (1985) gives occurrences in the *falciferum* and *tenuicostatum* Zones.

MATERIAL: 33 specimens.

Suborder **MILIOLINA** Delage and Hérouard, 1896

Superfamily **CORNUSPIRACEA** Schultze, 1854

Family **OPTHALMIDIIDAE** Wiesner, 1920

Genus *Opthalmidium* Kübler and Zwingli, 1870

Opthalmidum liascum (Kübler and Zwingli)

Pl. 1, Figs 25, 26.

1866 *Oculina liasica* Kübler and Zwingli, p. 11, pl. 1, fig. 24.

1946 *Opthalmidium liascum* (Kübler and Zwingli); Wood and Barnard, p. 84, fig. 1.

1969 *Opthalmidium orbiculare* Burbach; Brouwer, p. 27, pl. 2, figs 9-10.

1985 *Opthalmidium liascum* (Kübler and Zwingli); Riegraf, p. 103, pl. 6, fig. 36.

1989 *Opthalmidium liascum* (Kübler and Zwingli); Copestake and Johnson, p. 167, pl. 6.2.1, fig. 21.

DIAGNOSIS: A species of *Opthalmidium* with a small, thin, asymmetrical test with the adult chambers comprising 3/4 of a whorl. The test generally has a circular outline.

STRATIGRAPHICAL RANGE: Hettangian (*liascus* Zone) to Toarcian (*variabilis* Zone) becoming abundant in the *tenuicostatum* Zone (Copestake and Johnson, 1989).

MATERIAL: 56 specimens.

Opthalmidum macfadyeni Wood and Barnard

Pl. 1, Figs 23, 24.

1946 *Opthalmidium macfadyeni* Wood and Barnard, p. 92, pl. 9, figs a-g.

1989 *Opthalmidum macfadyeni* Wood and Barnard; Copestake and Johnson, p. 167, pl. 6.2.1, figs 18, 19.

DIAGNOSIS: A bilaterally symmetrical species of *Opthalmidium* with the chambers mostly of 1/2 whorl in length.

STRATIGRAPHICAL RANGE: Copestake and Johnson (1989) give a British range from Lower Sinemurian (*bucklandi* Zone) to Toarcian (*falciferum* Zone)

MATERIAL: 49 specimens.

Suborder **LAGENINA** Delage and Hérouard, 1896

Crystal units enveloped by organic membranes; primitive taxa without secondary lamination later ones secondarily lamellar. (Loeblich and Tappan, 1984).

Superfamily **NODOSARIACEA** Ehrenberg, 1838

Wall with both primary lamination and secondary lamination as a result of continued growth (Loeblich and Tappan, 1984).

Family **NODOSARIIDAE** Ehrenberg, 1838

Test free, multilocular, or rarely single chambered, chambers uniserial and rectilinear; wall calcareous, hyaline, finely perforate, monolamellar or ortho-monolamellar; aperture terminal, commonly radiate, or may be rounded, slit-like or multiple (Loeblich and Tappan, 1984).

Subfamily **NODOSARIINAE** Ehrenberg, 1838

Test with one or more chambers arranged in a straight series, uniserial or biserial. Aperture terminal, central, rounded, radiate or slit-shape. Emended (Copestake, 1978) to include LINGULININAE Loeblich and Tappan, 1961.

Genus *Frondicularia* Defrance, 1826

Frondicularia terquemi plexus

Frondicularia terquemi bicostata d'Orbigny

Pl. 4, Figs 2, 6, 11, 14.

1849 *Frondicularia bicostata* d'Orbigny, p. 242, no. 256.

1957 *Frondicularia sulcata* Form H Barnard, pl. 2, figs 11-12.

1957 *Spandelina bicostata* subsp. *bicostata* (d'Orbigny); Nørvang, p. 347,
figs 62-64, 67, 68.

1989 *Frondicularia terquemi bicostata* d'Orbigny; Copestake and Johnson,
p. 172, pl. 6.2.3, figs 1, 2.

DIAGNOSIS: A distinctive subspecies of *Frondicularia terquemi* that has a smooth median groove bordered by two distinct ribs usually with two or more reduced lateral ribs.

STRATIGRAPHICAL RANGE: A British range from Hettangian (*liascus* Zone) to top Pliensbachian is given by Copestake and Johnson (1989).

MATERIAL: 22 specimens.

Frondicularia terquemi muelensis Ruget and Sigal

Pl. 4, Figs 10, 12.

1970 *Frondicularia muelensis* Ruget and Sigal, p. 92, pl. 3, figs 19-32;
pl. 4, figs 1-6.

1957 *Frondicularia sulcata* Bornmann Form K; Barnard, pl. 2, figs 15-17.

1985 *Ichthyolaria squamosa* Terquem and Berthelin; Riegraf, p. 149, pl. 8, fig. 26.

1989 *Frondicularia terquemi muelensis* Ruget and Sigal; Copestake and Johnson,
p. 175, pl. 6.2.3, fig. 7.

DIAGNOSIS: A subspecies of *Frondicularia terquemi* with numerous fine, parallel striae and a compressed, non-sulcate test.

STRATIGRAPHICAL RANGE: Copestake and Johnson (1989) give a British range from the *raricostatum* Zone to top *tenuicostatum* Zone. This species is widespread in Europe.

MATERIAL: 27 specimens.

***Frondicularia terquemi* subsp. B.** Copestake and Johnson,

Pl. 4, Fig. 8

1936 *Frondicularia baueri* Burbach; Franke, pl. 7, fig. 10.

1969 *Frondicularia bicostata* d'Orbigny; Brouwer, pl. 5, figs 13-15.

1989 *Frondicularia terquemi* subsp. B Copestake and Johnson,

p. 174, pl. 6.2.3, fig. 4.

DIAGNOSIS: A robust subspecies of *Frondicularia terquemi* with four to six coarse, high costae confined to the central region of the test, bordered by lateral smooth area.

STRATIGRAPHICAL RANGE: Total range of *margaritatus* Zone to *tenuicostatum* Zone (Copestake and Johnson, 1989).

MATERIAL: 2 specimens.

Frondicularia terquemi sulcata Bornemann,

Pl. 4, Figs 3-5, 7, 9

1854 *Frondicularia sulcata* Bornemann, p. 37, pl. 3, fig. 22a, c.

1950a *Frondicularia sulcata* Barnard, p. 369, fig. 7a, e, f.

1989 *Frondicularia terquemi sulcata* Bornemann; Copestake and Johnson, pl. 6.2.3,

figs 6, 8-15.

DIAGNOSIS: A subspecies of the *Frondicularia terquemi* plexus that has a robust test with between four and 12 coarse longitudinal ribs which are either parallel, divergent or convergent. A median sulcus is occasionally present.

REMARKS: This subspecies contains the large, many ribbed forms of the *Frondicularia terquemi* plexus. The high variability in terms of rib number, rib orientation and test width have lead to many authors erecting new schemes of classification (Barnard, 1957; Nørvang, 1957; Norling, 1968). Copestake and Johnson (1989) consider that Barnard's 1957 morphological forms have the most stratigraphic usefulness and use Barnard's forms B-G.

STRATIGRAPHICAL RANGE: A consistent (not total) British range from the Hettangian (*liascus* Zone) to upper Pliensbachian (*margaritatus* Zone) is given by Copestake and Johnson (1989).

MATERIAL: 245 specimens.

Frondicularia terquemi terquemi d'Orbigny,

Pl. 4, Fig. 1.

1849 *Frondicularia terquemi* d'Orbigny, p. 241, no. 255.

1957 *Spandelina bicostata* (d'Orbigny) subsp. *terquemi* (d'Orbigny); Nørvang, p. 349, fig. 69.

1957 *Frondicularia sulcata* Bornemann form J; Barnard, p. 178, pl. 2, figs 18-19, 21.

1989 *Frondicularia terquemi terquemi* d'Orbigny; Copestake and Johnson, p. 175, pl. 6.2.3, fig. 16.

DIAGNOSIS: A smooth subspecies of *Frondicularia terquemi* that is identified by its lack of striae.

STRATIGRAPHICAL RANGE: Hettangian to Toarcian in Britain and N. W. Europe (Copestake and Johnson, 1989).

MATERIAL: 29 specimens.

Genus *Lingulina* d'Orbigny, 1826

Lingulina tenera Bornemann plexus

Members of this plexus of *Lingulina* posses a flaring parallel sided or pupiform test with a keeled or rounded periphery. The test is ribbed to some degree, usually with two main ribs and a strong tendency towards interstitial ribs to be added. A median longitudinal sinus may occur. The aperture is central and slit-like.

The *Lingulina tenera* plexus was originally described almost simultaneously by Barnard (1956) and Nørvang (1957) from the Lower Jurassic of England and Denmark respectively. The plexus has since been recognised by many workers (e.g. Ruget and Sigal, 1970; Brouwer, 1969; Norling, 1972) but treated in most detail by Johnson (1975) and Copestake (1979) during their study of the Mochras Borehole foraminifera. Copestake and Johnson (1989) figure the stratigraphically useful member of the plexus. The following subspecies of the *Lingulina tenera* plexus are recognised from the Lower Jurassic sections in this study and will treated more fully below:

Lingulina tenera plex. *collenoti*	(Terquem)
Lingulina tenera plex. *occidentalis*	(Berthelin)
Lingulina tenera plex. *pupa*	(Terquem)
Lingulina tenera plex. *substriata*	(Nørvang)
Lingulina tenera plex. *tenera*	Bornemann
Lingulina tenera plex. *tenuistriata*	(Nørvang)
Lingulina tenera plex. subsp. A	Copestake and Johnson

***Lingulina tenera* plex. *collenoti* (Terquem),**

Pl. 6, Fig. 18.

1866 *Marginulina collenoti* Terquem, p. 424, pl. 17, fig. 1 a-d.

1876 *Lingulina striata* Blake, p. 455, pl. 18, figs 16, 16a.

1956 *Lingulina tenera* Bornemann form A; Barnard, pl. 2; pl. 3, fig. 1.

1989 *Lingulina tenera* plex. *collenoti* (Terquem); Copestake and Johnson, p. 178, pl. 6.2.4, fig. 7.

DIAGNOSIS: A member of the *Lingulina tenera* plexus with an elongate, rounded test ornamented with fine, often discontinuous striae.

REMARKS: This form differs from *Lingulina tenera tenuistriata* in its lack of keel, and is the largest and most elongate member of the plexus.

STRATIGRAPHICAL RANGE: This species is an index for the basal Lower Jurassic. Copestake and Johnson (1989) give a total British range from uppermost Triassic to *angulata* Zone.

MATERIAL: 6 specimens.

Lingulina tenera* plex. *occidentalis **(Berthelin, 1879),**

Pl. 6, Fig. 1.

1879 *Frondicularia occidentalis* Berthelin, p. 34, pl. 1, figs 9-11.

1961 *Lingulina occidentalis* (Bethelin); Bizon and Oertli, p. 112, tab. 7.

1989 *Lingulina tenera* plex. *occidentalis* (Berthelin); Copestake and Johnson, p. 178, pl. 6.2.4, fig. 8.

DIAGNOSIS: A flattened subspecies of the *Lingulina tenera* plexus with sharp, arched and raised sutural ribs between two widely spaced longitudinal ribs.

REMARKS: The sutural ribs are distinctive. This subspecies was not recorded by Barnard or Nørvang. The specimen occurred in the *spinatum* Zone of Truc de Balduc and this species is regarded as a good indicator for the Pliensbachian by Copestake (1978).

STRATIGRAPHICAL RANGE: Copestake and Johnson (1989) give a range from *raricostatum* Zone to *tenuicostatum* Zone while Riegraf (1985) records occurrences in the *spinatum* and *tenuicostatum* Zones.

MATERIAL: 1 individual.

Lingulina tenera plex. *pupa* (Terquem),

Pl. 6, Figs 7- 9, 15-17, 20.

1866 *Marginulina pupa* Terquem, p. 429, pl. 17, fig. 7a-f.

1956 *Lingulina tenera* Bornemann forms I, H; Barnard, p. 274, pl. 3, figs 8-12.

1957 *Geinitzina tenera* (Bornemann) subsp. *pupa* (Terquem); Nørvang, p. 61, figs 32-43.

1957 *Geinitzina tenera* (Bornemann) subsp. *praepupa*; Nørvang, p. 60, figs 30, 31.

1972 *Geinitzinita tenera* (Bornemann); Norling, p. 97, fig. 51, A, B, E, F.

1989 *Lingulina tenera pupa* (Terquem); Copestake and Johnson, p. 178-9, pl. 6.2.4, fig. 13.

DIAGNOSIS: A subspecies of the *Lingulina tenera* plexus with a pupiform test lacking a keel but with typically constricted final chambers distinguishes this subspecies of the *Lingulina tenera* plexus. On each side of the test are 2 main longitudinal ribs between which are numerous slightly weaker ribs.

REMARKS: A long-ranging and widespread form, recovered from the Hettangian strata of East Quantoxhead to the Pliensbachian *margaritatus* Zone of Dorset and Tilton.

STRATIGRAPHICAL RANGE: British range Hettangian - Upper Toarcian (*levesquei* Zone) with an acme in the Lower Pliensbachian (Copestake and Johnson, 1989).

MATERIAL: 255 specimens.

Lingulina tenera plex. *substriata* (Nørvang),

Pl. 6, Fig. 6.

1957 *Geinitzina tenera* (Bornemann) subsp. *substriata* Nørvang, p. 333, figs 3-10.

1972 *Geinitzina tenera* (Bornemann) var. *substriata* Nørvang; Norling, p. 96, fig. 51c.

1978 *Lingulina tenera* plex. *substriata* (Nørvang); Copestake,
p. 398, pl. 16, figs 23, 24.

1989 *Lingulina tenera substriata* (Nørvang); Copestake and Johnson,
p. 179, pl. 6.2.4, fig. 12.

DIAGNOSIS: A keeled subspecies of the *Lingulina tenera* plexus that has an indistinct median sulcus. Its ribs are generally irregular and discontinuous. Two of the ribs tend to be stronger.

REMARKS: *Lingulina tenera* plex. *substriata*, in this study, has been found only in the Hettangian strata of East Quantoxhead.

STRATIGRAPHICAL RANGE: This form is a valuable index species for the Hettangian ranging from the base of this stage to just into the basal Sinemurian *bucklandi* Zone in Britain (Copestake and Johnson, 1989).

MATERIAL: 2 specimens.

***Lingulina tenera* plex. *tenera* (Bornemann)**

Pl. 6, Figs 5, 10-12, 21.

1854 *Lingulina tenera* Bornemann, p. 38, pl. 3, fig. 24a-c.

1858 *Frondicularia hexagona* Terquem, p. 35, pl. 1, fig. 13a-c.

1956 *Lingulina tenera* Bornemann forms B, D, E, G, J; Barnard, p. 275,
Pl. 1, figs 1, 2, 9a, b, 10a, b; pl. 3, figs 4, 5, 13.

1957 *Geinitzina tenera* (Bornemann) subsp. *tenera* (Bornemann); Nørvang, p. 58,
figs 18-23.

1957 *Geinitzina tenera* (Bornemann) subsp. *carinata*; Nørvang, p. 62, figs 46-48, 51.

1972 *Geinitzinita tenera* (Bornemann); Norling, p. 96, fig. 51 D, G.

1975 *Lingulina tenera tenera* Bornemann; Johnson, p. 351, pl. 19, figs 6, 12, 13, 15.

1989 *Lingulina tenera tenera* Bornemann; Copestake and Johnson,
p.179, pl. 6.2.4, fig. 9.

DIAGNOSIS: A subspecies of *Lingulina tenera* that has a median sulcus between two longitudinal ribs of variable strength and height with a keeled periphery and flush sutures.

REMARKS: The two strong ribs and lack of interstitial ribs or striae are diagnostic.

STRATIGRAPHICAL RANGE: Main range Rhaetian to Toarcian with a distinct acme in Britain in the upper *angulata* Zone (Copestake and Johnson, 1989).

MATERIAL: 1812 specimens.

***Lingulina tenera* plex. *tenuistriata* (Nørvang),**

Pl. 6, Figs 13, 14, 19.

1876 *Lingulina tenera* Bornemann; Blake, p. 455, pl. 18, fig. 15.

1956 *Lingulina tenera* Bornemann form F; Barnard, p. 275, pl. 3, fig. 6.

1957 *Geinitzina tenera* (Bornemann) subsp. *tenuistriata*; Nørvang, p. 56,
figs 13, 16, 17, 24.

DIAGNOSIS: A subspecies of the *Lingulina tenera* plexus with a broad or elongate test with a keel and a median sulcus. Ornament comprises 2 strong main ribs on each side of the test, with numerous striations which are fine and discontinuous.

STRATIGRAPHICAL RANGE: British range from Rhaetian to Upper Toarcian, most abundant in the *bucklandi* to *semicostatum* Zones (Copestake and Johnson, 1989).

MATERIAL: 480 specimens.

***Lingulina tenera* plex. subsp. A (Copestake and Johnson),**

Pl. 6, Figs 2-4.

1989 *Lingulina tenera* subsp. A; Copestake and Johnson, p. 180, pl. 6.2.4, fig. 14.

DIAGNOSIS: A subspecies of *Lingulina tenera* that is distinguished by its broad, flattened test with a slight median sulcus bordered by two longitudinal raised areas. The margin is rounded and smooth.

REMARKS: The almost smooth test is distinctive. This form appears in the *margaritatus* Zone at Tilton.

STRATIGRAPHICAL RANGE: The main occurrences are in the Upper Pliensbachian. occurring most consistently in the *margaritatus* Zone (Copestake and Johnson, 1989).

MATERIAL: 249 specimens.

Genus *Nodosaria* Lamarck, 1812

Nodosaria dispar Franke

Pl. 8, Figs 8, 9.

1936 *Nodosaria dispar* Franke, pp. 39, 40, 47, pl. 4, fig. 18a-d

1957 *Nodosaria dispar* Franke; Nørvang, p. 356, figs 80, 81.

1972 *Nodosaria dispar* Franke; Norling, p. 47, figs 18 A_1-A_3, 19A.

1978 *Nodosaria dispar* Franke; Copestake, p. 326, pl. 9, figs 16, 18-22, 24-26.

DIAGNOSIS: A distinctive species of *Nodosaria* that is short and robust, circular in section with nearly parallel sides. The test is ornamented with 8-10 distinct ribs traversing the test from the proloculus on to the apertural margin. The aperture is terminal, central and produced where the rib ends merge to form an elevated rim.

STRATIGRAPHICAL RANGE: Norling (1972) reports a range of Hettangian to Toarcian with rare occurrences in the Aalenian.

MATERIAL: 11 specimens.

Nodosaria fontinensis Terquem,

Pl. 8, Fig. 7.

1870 *Nodosaria fontinensis* Terquem, p. 251, pl. 26, figs 1, 5.

1957 *Nodosaria fontinensis* Terquem; Nørvang, p. 356, fig. 79.

1978 *Nodosaria fontinensis* Terquem; Copestake, p. 326, pl. 9, figs 30, 31.

DIAGNOSIS: A species of *Nodosaria* that has constricted sutures and an apertural chamber that is higher than broad. The test is ornamented with low and broad ribs which are depressed between the chambers. The aperture is radiate without a distinct apertural neck.

STRATIGRAPHICAL RANGE: Nørvang (1957) gives occurrences throughout the Lower Jurassic.

MATERIAL: 38 specimens.

Nodosaria kuhni Franke,

Pl. 8, Fig. 10.

1936 *Nodosaria kuhni* Franke, p. 46, pl. 4, fig. 13.

1978 *Nodosaria kuhni* Franke; Copestake, p. 327, pl. 10, figs 16-18.

1985 *Nodosaria kuhni* Franke; Riegraf, p. 106, pl. 7, fig. 15.

DIAGNOSIS: A species of *Nodosaria* with interrupted ribs, absent over most of each chamber extending across the sutures only. The final chamber is commonly inflated and larger than the previous 4 chambers.

STRATIGRAPHICAL RANGE: Riegraf (1985) gives occurrences from the Upper Pliensbachian to Lower Toarcian (*tenuicostatum* Zone).

MATERIAL: 5 specimens.

Nodosaria metensis Terquem,

Pl. 8, Figs 1-2.

1864 *Nodosaria metensis* Terquem, p. 377, pl. 7, fig. 5a, b.

1950 *Nodosaria metensis* Terquem; Barnard, p. 355, fig. 4f.

1957 *Nodosaria metensis* Terquem; Nørvang, p. 352, fig. 72.

1969 *Nodosaria metensis* Terquem; Brouwer, p. 28, pl. 3, fig. 12.

DIAGNOSIS: An highly ornamented species of *Nodosaria* that has a test of 5 or 6 chambers with numerous fine, low ribs which run from the base of the proloculus all over the test up to the apertural neck. The aperture is produced on short neck.

STRATIGRAPHIC RANGE: Nørvang (1957) records occurrences throughout the Lower Jurassic, while Brouwer (1969) gives a range from the Hettangian to Toarcian.

MATERIAL: 53 specimens.

Nodosaria mitis (Terquem and Berthelin),

Pl. 8, Fig. 6.

1875 *Dentalina mitis* Terquem and Berthelin, p. 28, pl. 2, fig. 9a-c.

1875 *Dentalina oculina* Terquem and Berthelin, p. 31, pl. 2, fig. 20 a-c.

1936 *Nodosaria mitis* (Terquem and Berthelin); Franke, p. 45, pl. 4, fig. 11a.

1936 *Nodosaria oculina* (Terquem and Berthelin); Franke, p. 49, pl. 4, fig. 21.

1955 *Nodosaria mitis* (Terquem and Berthelin); Tappan, p. 70, pl. 24, figs 11-18.

1957 *Nodosaria oculina* (Terquem and Berthelin); Nørvang, p. 77, fig. 77.

1957 *Nodosaria mitis* (Terquem and Berthelin); Nørvang, p. 76, fig. 74.

1969 *Nodosaria oculina* (Terquem and Berthelin); Brouwer, p. 28, pl. 3, fig. 13.

1972 *Nodosaria mitis* (Terquem and Berthelin); Norling, p. 49, figs 18C_1-C_3, 20 A-D.

DIAGNOSIS: A species of Nodosaria with high flange-like ribs that continue uninterrupted across chambers and sutures. The slightly tapering test is narrow and elongate.

REMARKS: This species was originally described as belonging to *Dentalina* and some specimens have been reported which have a curved axis (Tappan, 1955), but the species is placed in *Nodosaria* as the specimens most frequently nodosarian in character. Tappan (1955) considered *Dentalina mitis* and *D. oculina* to be synonyms and according to the rules of nomenclature, the first used name is the only valid one. The species is therefore known as *Nodosaria mitis* (Terquem and Berthelin).

STRATIGRAPHICAL RANGE: *liascus* Zone to uppermost Toarcian (Copestake and Johnson, 1989).

MATERIAL: 3 specimens.

Nodosaria nitidana Brand,

Pl. 8, Figs 3, 4.

1937 *Nodosaria nitidana* Brand; Bartenstein and Brand, p. 143, pl. 2, fig. 22; pl. 4, fig. 32; pl. 5, fig. 27.

1950a *Nodosaria nitidana* Brand; Barnard, p. 357, fig. 4g.

1978 *Nodosaria nitidana* Brand; Copestake, p. 298, pl. 9, figs 31, 32.

DIAGNOSIS: A smooth species of *Nodosaria* that consists of a rectilinear series of almost spherical chambers which are variable in size. Constrictions at the sutures vary greatly but are usually moderately deep, so that the chambers have a bulbous spherical appearance. The final chamber is slightly drawn out to a central aperture.

STRATIGRAPHICAL RANGE: *angulata* Zone to uppermost Toarcian (Copestake and Johnson, 1989).

MATERIAL: 105 specimens.

Nodosaria simplex (Terquem),

Pl. 9, Fig. 5.

1858 *Dentalina simplex* Terquem, p. 39, pl. 2, fig. 5a, b.

1950a *Nodosaria simplex* (Terquem); Barnard, p. 359, fig. 4h.

1978 *Nodosaria simplex* (Terquem); Copestake, p. 328, pl. 11, figs 19, 22.

1985 *Nodosaria simplex* (Terquem); Riegraf, p. 104, pl. 7, fig. 1.

DIAGNOSIS: A small, smooth species of *Nodosaria* with 5-7 chambers which are initially spherical but increase in height during growth. The final chamber is drawn out and the test is parallel sided or slightly divergent. The aperture is round and flush with the surface.

STRATIGRAPHICAL RANGE: *Nodosaria simplex* ranges between the Hettangian and the Toarcian in N. W. Europe (Copestake, 1978).

MATERIAL: 117 specimens.

Genus *Pseudonodosaria* Boomgart, 1949

Pseudonodosaria vulgata (Bornemann),

Pl. 8, Figs 11-13.

1854 *Glandulina vulgata* Bornemann, p. 31, pl. 2, fig. 1a, b.

1936 *Glandulina vulgata* Bornemann; Franke, p. 54, pl. 5, fig. 9a, b.

1950 *Pseudoglandulina vulgata* Barnard, p. 365, fig. 4c.

1957 *Pseudonodosaria vulgata* (Bornemann); Nørvang, p. 358, fig. 85.

1972 *Pseudonodosaria* ex gr. *vulgata* (Bornemann); Norling, p. 86, fig. 46a-c.

1985 *Pseudonodosaria vulgata* (Bornemann); Riegraf, p.110, pl. 10, fig. 30.

1989 *Pseudonodosaria vulgata* (Bornemann); Copestake and Johnson, pp.183-4, pl. 6.2.5, figs 12, 13.

DIAGNOSIS: A smooth species of *Pseudonodosaria* that is oviform to conical in shape with the chambers gradually increasing in size. The sutures are indistinct while the aperture is radiate and produced.

REMARKS: The wide variety of forms within this species has been dealt with by Barnard (1951) and Norling (1972).

STRATIGRAPHICAL RANGE: Common throughout the Lower Jurassic of Europe, first appearing in the *liascus* Zone (Copestake and Johnson, 1989).

MATERIAL: 76 specimens.

Genus *Lagena* Walker and Jacob, 1768

Lagena aphela Tappan,

Pl. 8, Fig. 14.

1955 *Lagena aphela* Tappan, p. 82, pl. 28, figs 13-14.

1978 *Lagena aphela* Tappan; Copestake, p. 296, pl. 12, figs 1, 4.

DIAGNOSIS: A small species of *Lagena* that is spherical to ovate in shape and has a slightly produced aperture.

STRATIGRAPHICAL RANGE: *liascus* Zone to uppermost Toarcian (Copestake, 1978).

MATERIAL: 52 specimens.

Subfamily **VAGINULININAE** Reuss, 1860

Emended (Copestake, 1978) to include curved genera only. The chambers are arranged in a curved or arcuate series. Test morphology can be oval, triangular, rounded or compressed in cross-section. The aperture is radiate or round and situated at the dorsal margin.

Genus *Citharina* d'Orbigny, 1839

Citharina colliezi (Terquem),

Pl. 2, Fig. 12

1866 *Marginulina colliezi* Terquem, p. 430, pl. 27, fig. 10a, b, c.

1950b *Citharina colliezi* (Terquem); Barnard, p. 14, pl. 3, fig. 1.

1981 *Citharina colliezi* (Terquem); Copestake and Johnson, p. 92, pl. 6.1.2, fig. 2.

1985 *Citharina gradata* (Terquem); Riegraf, p. 138, pl. 8, figs 19-20.

1990 *Citharina colliezi* (Terquem); Muller, p. 195, pl. 9, fig. 10.

DIAGNOSIS: A large species of *Citharina* that is triangular in shape and compressed. The surface of the test is ornamented by numerous ribs running longitudinally along each chamber.

STRATIGRAPHICAL RANGE: Probable age of Toarcian to Early Bajocian (Copestake and Johnson, 1989).

MATERIAL: 3 specimens.

Genus *Dentalina* Risso, 1826

Dentalina irregularis Terquem,

Pl. 3. Fig. 12.

1862 *Dentalina irregularis* Terquem, p. 442, pl. 5, fig. 21.

1950b *Dentalina vetustissima* Terquem; Barnard, p. 20, fig. 12.

1985 *Dentalina irregularis* Terquem; Riegraf, p. 113, pl. 7, figs 32, 33.

DIAGNOSIS: A species of *Dentalina* with an irregular chamber arrangement of early barrel shaped chambers and later ellipsoidal, tapered chambers.

REMARKS: The chambers also differ in their height and breadth.

STRATIGRAPHICAL RANGE: Riegraf records occurrences in the *spinatum* Zone.

MATERIAL: 4 specimens.

Dentalina matutina d'Orbigny, 1849,

Pl. 3, Figs 7, 8.

1849 *Dentalina matutina* d'Orbigny, p. 243, no. 259.

1978 *Dentalina matutina* (d'Orbigny); Copestake, p. 439, pl. 19, figs 15-19.

DIAGNOSIS: A robust, elongated species of *Dentalina* that is ornamented with coarse, oblique costae. The aperture is produced and radiate.

STRATIGRAPHICAL RANGE: This species is reported to range between the Hettangian and Lower Bajocian (Copestake, 1978).

MATERIAL: 270 specimens.

Dentalina vetustissima d'Orbigny,

Pl. 3, Fig. 9.

1849 *Dentalina vetustissima* d'Orbigny, p. 242, no. 261.

1936 *Dentalina vetustissima* d'Orbigny; Macfadyen, p. 150, pl. 1, fig. 261.

1985 *Dentalina propinqua* Terquem; Riegraf, p. 114, pl. 7, figs 49-50.

DIAGNOSIS: A species of *Dentalina* that consists of a linear, either straight or slightly arcuate, series of four to six chambers. The early chambers are barrel-shaped while later ones are more ellipsoidal.

STRATIGRAPHICAL RANGE: *angulata* Zone to uppermost Toarcian (Copestake, 1978).

MATERIAL: 18 specimens.

Dentalina pseudocommunis Franke,

Pl. 3, Figs 5, 6.

1936 *Dentalina pseudocommunis* Franke, p. 30, pl. 2, fig. 20a, b.

1941 *Dentalina communis* d'Orbigny; Macfadyen, p. 39, pl. 2, fig. 34.

1950b *Dentalina pseudocommunis* Franke; Barnard, p. 19, pl. 3, figs 6, 7, text-fig. 11.

DIAGNOSIS: A species of *Dentalina* comprising six to ten chambers arranged in a linear series to form a slender elongate, curved test. After the first few, the chambers increase rapidly in height but only slightly in breadth.

STRATIGRAPHICAL RANGE: *liascus* Zone to uppermost Toarcian (Copestake, 1978).

MATERIAL: 169 specimens.

Dentalina terquemi d'Orbigny, 1849,

Pl. 3, Figs 3, 4.

1849 *Dentalina terquiemi* d'Orbigny, pl. 2, figs 5-7; pl. 6, fig. 10.

1968 *Prodentalina terquemi* (d'Orbigny); Norling, p. 36, pl. 3, figs 1, 3.

1985 *Dentalina terquemi* (d'Orbigny); Riegraf, p. 115, pl. 7, figs 51-52.

1989 *Dentalina terquemi* (d'Orbigny); Copestake and Johnson, p. 171, pl. 6.2.2, fig. 14.

DIAGNOSIS: A large robust species of *Dentalina* comprising 10-12 smooth cylindrical chambers with horizontal, flush sutures and the aperture on a drawn out neck.

REMARKS: Most individuals examined were closest to the variants described by Barnard (1950a), and had constricted chambers in the final portion of the test.

STRATIGRAPHICAL RANGE: British range Hettangian to top Pliensbachian with acmes in the *semicostatum* Zone, *obtusum* Zone and Upper Pliensbachian (Copestake and Johnson, 1989).

MATERIAL: 122 specimens.

Dentalina tortilis Franke,

Pl. 3, Fig. 10.

1936 *Dentalina tortilis* Franke, p. 29, pl. 2, fig. 19a-b.

1955 *Dentalina tortilis* Franke; Tappan, p. 68, pl. 21, figs 23-25.

DIAGNOSIS: A distinctive species of *Dentalina* that has an elongate, tapering test with an eccentric basal spine. Later chambers are inflated with a final chamber that is comparatively high and inflated. The test wall is smooth with flush sutures. The aperture is radiate, on a short neck at the inner margin of the test.

STRATIGRAPHICAL RANGE: Tappan (1955) records occurrences of Late Pliensbachian age.

MATERIAL: 12 specimens.

Dentalina varians Terquem,

Pl. 3, Fig. 11.

1866 *Dentalina varians* Terquem, p. 485, pl. 19, figs 26-27.

1985 *Dentalina varians* Terquem; Riegraf, p. 113, pl. 7, figs 43-44.

DIAGNOSIS: A delicate species of *Dentalina* that has a smooth, slender test with elongate chambers and deep sub-horizontal sutures.

STRATIGRAPHICAL RANGE: Sinemurian to Lower Toarcian (Riegraf, 1985).

MATERIAL: 266 specimens.

Dentalina vetusta d'Orbigny,

Pl. 3, Figs 1, 2.

1850 *Dentalina vetusta* d'Orbigny, p. 242, no. 258.

1876 *Dentalina communis* d'Orbigny; Blake in Tate and Blake, p. 457, pl. 18, fig. 19.

1936 *Dentalina vetusta* d'Orbigny; Macfadyen, p. 150, pl. 1, fig. 258.

1985 *Dentalina vestusta* d'Orbigny; Riegraf, p. 116, pl. 7, figs 47-48.

DIAGNOSIS: A smooth species of *Dentalina* with flush sutures and an elongate final chamber.

STRATIGRAPHICAL RANGE: Riegraf (1985) records occurrences in the Lower Toarcian.

MATERIAL: 70 specimens.

Genus *Vaginulina* d'Orbigny, 1826

Vaginulina listi (Bornemann),

Pl. 9, Fig. 1.

1854 *Cristellaria listi* Bornemann, pl. 4, fig. 28.

1957 *Vaginulina listi* (Bornemann); Nørvang, p. 370, fig. 119.

1969 *Vaginulina listi* (Bornemann); Brouwer, pp. 10, 11, 40, table 2;
pl. 3, figs 19-23.

1972 *Vaginulina listi* (Bornemann); Norling, p. 94, fig. 49a, b.

1989 *Vaginulina listi* (Bornemann); Copestake and Johnson, p. 186, pl. 6.2.6, fig. 10.

DIAGNOSIS: A species of *Vaginulina* that has a smooth test which is slightly curved towards the dorsal side. The test has an initial curved (not coiled) portion followed by an elongate rectilinear portion with indistinct sutures.

STRATIGRAPHICAL RANGE: First British appearance during the *semicostatum* Zone, ranging to the top of the Toarcian (Copestake and Johnson, 1989).

MATERIAL: 4 specimens.

Vaginulina simplex Terquem,

Pl. 9. Fig. 2.

1863 *Vaginulina simplex* Terquem, p. 184, pl. 8, fig. 1a, b.

1950a *Vaginulina simplex* Terquem; Barnard, p. 373, pl. 8, fig. e.

1985 *Vaginulina simplex* Terquem; Riegraf, p. 142, pl. 10, fig. 53.

DIAGNOSIS: A species of *Vaginulina* with constricted, oblique sutures that slope away from the apertural margin down towards the initial end of the test. The small elongate ellipsoidal proloculum is followed by chambers with a dentaline form.

STRATIGRAPHICAL RANGE: Barnard (1950a) and Riegraf (1985) record occurrences in the *tenuicostatum* Zone.

MATERIAL: 10 specimens.

Subfamily **LENTICULININAE** Chapman, Parr and Collins, 1934

Emended (Copestake, 1978) to include MARGINULININAE Wedekind, 1937. Chambers coiled at some stage, either coiled throughout or with initial coil followed by rectilinear or curvilinear uncoiled portion. The cross-sectional shape is round, ovate, flattened or triangular. Aperture central, eccentric or marginal.

Genus *Astacolus* de Montfort, 1808

Test elongate to ovate in outline, flattened, chambers numerous, broad and low, added on a slightly curved axis or may be distinctly enrolled in the very early stage, later uncoiling, with strongly oblique, straight to curved or sinuate sutures, periphery rounded to angular. Surface smooth; aperture radiate, at the dorsal angle.

Astacolus / Vaginulinopsis speciosa (Terquem),

Pl. 2, Figs 4, 6.

1858 *Cristellaria speciosa* Terquem, p. 64, pl. 4, fig. 2a, b.

1936 *Cristellaria (Astacolus) radiata* Franke, p. 108, pl. 11, fig. 3.

1950a *Marginulina undulata* Barnard, p. 372, fig. 5f (non Terquem).

1957 *Marginulinopsis radiata* (Franke non Terquem); Nørvang, p. 371, figs 105, 107.

1972 *Astacolus neoradiata* Neuweiler; Norling, p. 55, fig. 24a-d.

1972 *Astacolus quadricostata* (Terquem); Norling, p. 56, fig. 26a-c.

1978 *Astacolus / Vaginulinopsis speciosa* (Terquem); Copestake, p. 493,
pl. 23, figs 5-9.

DIAGNOSIS: A variable species of *Astacolus* that has 2 - 7 oblique intermittent ribs on each side of the test which is usually compressed, ovate or rectangular in section. The indistinct coiled portion is followed by an elongate, parallel-sided rectilinear portion.

REMARKS: The complicated taxonomy and variation of this species has been discussed by Copestake (1978) who attempted to clarify the classification with the observation that owing to the variation its true generic position is not always obvious. Specimens can be referred to either *Astacolus* or *Vaginulinopsis*, depending upon the test width and degree of lateral compression. The species is therefore referred to *Astacolus / Vaginulinopsis* as the astacoline forms are the commonest, taking into account the variation. The assignment to *Marginulina* is erroneous as specimens are never rounded in cross-section.

STRATIGRAPHICAL RANGE: *angulata* Zone to *levesquei* Zone (Copestake, 1978).

MATERIAL: 104 specimens.

Astacolus pauperatus (Jones and Parker),

Pl. 2, Figs 1, 9.

1860 *Planularia pauperata* Jones and Parker, p. 454, pl. 20, fig. 39.

1950b *Planularia pauperata* Jones and Parker; Barnard, p. 10, pl. 2, fig. 7, text figs 3, 4.

1957 *Planularia pseudocrepidula* Adams, pp. 208-213, text-figs 1-5.

1969 *Astacolus pauperatus* (Jones and Parker); Brouwer, p. 29, pl. 6, figs 22-25.

DIAGNOSIS: A very variable species of *Astacolus* that is compressed with shallow, oblique sutures which curve at both ends. The coiled portion of the test is rapidly replaced by the rectilinear growth.

REMARKS: Barnard (1950b) and Adams (1957) give good descriptions of the varied morphology of this species.

STRATIGRAPHICAL RANGE: Upper Pliensbachian to Lower Aalenian (Brouwer, 1969).

MATERIAL: 94 specimens.

Astacolus pediacus Tappan,

Pl. 2, Fig. 8.

1955 *Astacolus pediacus* Tappan, p. 56, pl. 17, figs 1-10.

DIAGNOSIS: A distinctive species of *Astacolus* that has an elongate, flattened test with an early coiled portion. The chambers are low and broad, extending backwards at the inner margin. The sutures are distinct and slightly curved.

REMARKS: This species can resemble *Planularia protracta* (Bornemann) but is distinguished by being larger and broader.

STRATIGRAPHICAL RANGE: Tappan (1955) records occurrences in the Early Jurassic and the Lower Toarcian.

MATERIAL: 14 specimens.

Astacolus primus d'Orbigny,

Pl. 2, Figs 2, 10, 11.

1849 *Cristellaria prima* d'Orbigny, p. 242, no. 266.

1950a *Planularia protracta* (Bornemann); Barnard, p. 376, fig. 8h.

1957 *Marginulinopsis prima* (d'Orbigny); Nørvang, p. 376, figs 116, 121, 122.

1957 *Marginulinopsis matutina* (d'Orbigny); Nørvang, p. 374, figs 115, 117.

1960 *Lenticulina varians* form F Barnard, p. 43, pl. 2, figs 13-15; pl. 5, figs 1-6.

1969 *Astacolus primus* (d'Orbigny); Brouwer, p. 30, pl. 4, figs 6-8.

1972 *Astacolus prima* (d'Orbigny); Norling, p. 56, fig. 25 A-D.

1975 *Astacolus primus* (d'Orbigny); Johnson, p. 396, pl. 14, figs 6, 10.

DIAGNOSIS: A robust species of *Astacolus* with an initially coiled, later curved series of chambers. The test is smooth with flush or depressed sutures.

REMARKS: This species has a sharp edge which may develop from the slight keel formed on the initial coiling portion. There is considerable variation within this species (Brouwer, 1969).

STRATIGRAPHICAL RANGE: Brouwer (1969) records a range of Hettangian to Lower Aalenian.

MATERIAL: 225 specimens.

Genus *Lenticulina* Lamark, 1804

Test enrolled, generally planispiral; commonly with umbonal boss, periphery angled to carinate, relatively broad and low chambers increase slowly in size as added or final one or two may tend to flare or uncoil, sutures straight to curved, radial or oblique, may be limbate, flush or elevated and nodose. Surface smooth other than the sutural nodes or elevations and peripheral keel; aperture radiate or slit-like at the peripheral angle, may be slightly produced.

Lenticulina d'Orbigny Roemer 1839,

Pl. 5, Fig. 1.

1839 *Peneroplis d'orbignyi* Roemer, p. 47, pl. 20, fig. 31.
1985 *Astacolus dorbignyi* (Roemer); Riegraf, p. 119, pl. 8, fig. 9.
1989 *Lenticulina dorbignyi* (Roemer); Copestake & Johnson, p. 176, pl. 6.2.4, fig. 1.

DIAGNOSIS: A loosely-coiled species of *Lenticulina* with a reticulate ornament covering the whole test.

REMARKS: This species first appears in the *levesquei* Zone at Eype.

STRATIGRAPHICAL RANGE: Copestake and Johnson (1989) give a total range of Lower Toarcian (? *falciferum* Zone, Ruget, 1988) to Lower Bajocian.

MATERIAL: 12 individuals

Lenticulina foveolata (Franke),

Pl. 5, Figs 6, 7.

1936 *Cristellaria (Lenticulina) foveolata* Franke, p. 115, pl. 11, fig. 20.

1949 *Lenticulina foveolata* Franke; Brand, pl. 14.

1985 *Lenticulina foveolata* Franke; Riegraf, p. 124, pl. 9, figs 10,11.

DIAGNOSIS: A species of *Lenticulina* that has a delicate test with distinct radial ribs merging in the umbilicus with a tendency towards a polygonal outline.

REMARKS: This species has not been described from the UK but was recorded by Riegraf (1985) as occurring in SW Germany and southern France. It is distinguished from the *Lenticulina muensteri* plexus group by its more delicate test, lack of umbilical boss and merging radial ribs.

STRATIGRAPHICAL RANGE: This species first appears in the *fibulatum* Subzone, Riegraf (1985). Total range not known.

MATERIAL: 46 specimens.

Lenticulina muensteri (Roemer) plexus group

DIAGNOSIS: A species of *Lenticulina* with an inflated, closely coiled test. The margins may be rounded or indistinctly keeled with a smooth surface and flush sutures.

REMARKS: The *Lenticulina muensteri* plexus is a polymorphic species group common in the European Jurassic containing at least four closely related subspecies: *muensteri, acutiangulata, polygonata, subalata* (Copestake and Johnson, 1989). These forms have been noted by a wide range of workers from Denmark (Nørvang, 1957), Mochras borehole (Johnson, 1975; Copestake, 1979), Germany (Riegraf, 1985), and more broadly, over Europe (Brouwer, 1969). The stratigraphical range of this group is given by Copestake (1978) as *liascus* Zone to uppermost Toarcian.

Members of this plexus group often occur with *Lenticulina varians* gr. but is distinguished by being more tightly coiled, generally broader and more robust and by the possession of umbilical plugs, bosses and occasional polygonal outlines.

Lenticulina muensteri muensteri (Roemer),

Pl. 5, Figs 2, 3.

1839 *Robulina muensteri* Roemer, p.48, pl. 20, fig. 29.

1957 *Lenticulina gottingensis* (Bornemann); Nørvang, p. 382, figs 153-162, 167-169.

1960 *Lenticulina* form D, F, G, I Barnard, pl. 1, figs 14, pl. 2, figs 9-15,
pl. 3, figs 1, 2, pl. 3, figs 8-10, pl. 5, figs, 1-10, 16.

1975 *Lenticulina muensteri muensteri* (Roemer); Johnson, pl. 11, figs 4, 12.

1985 *Lenticulina gottingensis* (Bornemann); Riegraf, p. pl. 8, figs 29-30.

1989 *Lenticulina muensteri muensteri* (Roemer); Copestake and Johnson, p. 178, pl. 6.2.4, fig. 2.

DIAGNOSIS: A subspecies of *Lenticulina muensteri* that has a large, robust, smooth test with an angular margin. The flush sutures merge into a smooth umbilical area. There are seven to ten chambers in the final whorl of planispiral forms while uncoiled forms have a well-developed, parallel sided portion of three to six chambers.

STRATIGRAPHICAL RANGE: This subspecies occurs from the *obtusum* Zone of the Sinemurian through to the Upper Aalenian (Brouwer, 1969; Copestake and Johnson, 1989)

MATERIAL: 1655 specimens.

Lenticulina muensteri acutiangulata (Terquem),

Pl. 5, Figs 5, 15.

1864 *Robulina acutiangulata* Terquem, p. 220, pl. 10, fig. 20a, b.

1936 *Cristellaria (Lenticulina) acutiangulata* Franke, p. 117, pl. 11, fig. 25.

1957 *Lenticulina acutiangulata* (Terquem); Nørvang, p. 383, figs 177, 178.

1985 *Lenticulina impressa* (Terquem); Riegraf, pp. 122-123, pl. 8, figs 33-34.

1979 *Lenticulina muensteri acutiangulata* (Terquem); Johnson, pl. 11, figs 1, 3, 10.

1989 *Lenticulina muensteri acutiangulata* (Terquem); Copestake and Johnson, p. 176, pl. 6.2.4, fig. 6.

DIAGNOSIS: A subspecies of *Lenticulina muensteri* that is distinguished by its smooth test with a sharply keeled periphery and protruding umbilical boss. Sutures are flush, with seven to eight chambers in the final whorl.

STRATIGRAPHICAL RANGE: Total range of Lower Pliensbachian to Oxfordian, throughout Europe with an acme in the *margaritatus* Zone (Copestake and Johnson, 1989).

MATERIAL: 372 specimens.

Lenticulina muensteri polygonata (Franke),

Pl. 5, Fig. 14.

1936 *Cristellaria (Lenticulina) polygonata* Franke, p. 118, pl. 12, figs 1,2.

1957 *Lenticulina polygonata* Franke; Nørvang, p. 383, fig. 179.

1975 *Lenticulina muensteri polygonata* (Franke); Johnson, pl. 11, fig. 6.

1985 *Lenticulina polygonata* (Franke); Riegraf, pp. 123-124, pl. 9, figs 2-3.

DIAGNOSIS: A subspecies of *Lenticulina muensteri* with a distinctive polygonal outline.

STRATIGRAPHICAL RANGE: Upper Pliensbachian to Upper Toarcian (Riegraf, 1985).

MATERIAL: 151 specimens.

Lenticulina muensteri subalata (Reuss),

Pl. 5, Figs 9, 11, 13.

1854 *Cristellaria subalata* Reuss, p. 68, pl. 25, fig. 13.

1975 *Lenticulina muensteri subalata* Johnson, pl. 11, figs 2, 5.

1985 *Lenticulina helios* (Terquem); Riegraf, p. 124, pl. 9, fig. 8.

DIAGNOSIS: This subspecies of *Lenticulina muensteri* has clear radial ribs that merge with an umbilical boss.

STRATIGRAPHICAL RANGE: Riegraf (1985) gives a total range of *bifrons* Zone through to the Callovian.

MATERIAL: 255 specimens.

Lenticulina varians (Bornemann) plexus,

Pl. 5, Figs 4, 8, 10, 14.

1854 *Cristellaria varians* Bornemann, p. 41, pl. 4., figs 32-34.

1908 *Cristellaria major* Issler, p. 80, pl. 5, figs 249, 250.

1936 *Cristellaria (Lenticulina) varians* Franke, p. 112, pl. 11, figs 9-11.

1957 *Astacolus varians* (Bornemann); Nørvang, p. 377, figs 123-124.

1960 *Lenticulina* forms A, B, C, Barnard, pp. 45-46, pl. 1, figs 1-13; pl. 4, figs 1-13.

1960 *Lenticulina varians* (Bornemann); Barnard, p. 45, pl. 6, figs 1-9; pl. 7, figs 1-10.

1979 *Lenticulina varians* (Bornemann) gr. ; Copestake, 1979. pl. 23, figs 24-29.

1989 *Lenticulina varians* (Bornemann) plexus; Copestake and Johnson, p. 176, pl. 6.2.4, fig. 3.

DIAGNOSIS: A compressed, variable, species of *Lenticulina* with an auriculate outline, comprising up to 15 high, broad chambers, with a strong tendency to uncoiling. The sutures are flush or raised and the margin rounded or keeled.

REMARKS: A variable species which shows a strong tendency towards uncoiling with uncoiled forms and coiled forms re-occurring throughout the Lower Jurassic. A wide variety of forms have been described by Barnard (1950a, b) most of which belong to this plexus. Extensive reference lists, embracing the various forms of the plexus, were given by Macfadyen (1941) and Nørvang (1957). *Lenticulina varians* differs from *Lenticulina muensteri* in being more loosely coiled, more compressed and in lacking an umbilical boss.

STRATIGRAPHICAL RANGE: Rhaetian to Oxfordian, first appearing in Britain in the *liascus* Zone (Copestake and Johnson, 1989).

MATERIAL: 683 specimens.

Genus *Marginulina* d'Orbigny, 1826

Marginulina alata **Terquem,**

Pl. 7, Figs 13, 14.

1858 *Marginulina alata* Terquem, p. 56, pl. 3, fig. 9.

1863 *Marginulina burgundiae* Terquem, p. 196, pl. 9, fig. 3a-d.

1972 *Marginulina prima* d'Orbigny, var. *burgundiae* Terquem; Norling, p. 75, fig. 42B-E.

1985 *Marginulina alata* Terquem; Riegraf, p. 132, pl. 9, figs 35, 36.

DIAGNOSIS: An elongate species of *Marginulina* that is formed of chambers that increase gradually in size. The initial chambers are small and either in an open coil or in a slightly curved series. Later chambers are rectilinearly arranged with indistinct sutures. The test is ornamented with strong longitudinal ribs. The aperture is eccentric and the apertural face is thickened.

REMARKS: Nørvang (1957) considered this species was not connected, by passage forms, with the various subspecies of *M. prima*. The specimens recovered during this study all came from the Dotternhausen samples. Riegraf (1985) also recognised this species from Dotternhausen, separating it from *Marginulina prima*. The test is slimmer than *M. prima* and the ribs thicken around the apertural face.

STRATIGRAPHICAL RANGE: Sinemurian to uppermost Toarcian (Riegraf, 1985).

MATERIAL: 24 specimens.

Marginulina prima insignis **(Franke),**

Pl. 7, Figs 1, 2.

1936 *Dentalina insignis* Franke, pl. 3, fig. 11a-b.

1989 *Marginulina prima insignis* (Franke); Copestake and Johnson, p. 180, pl. 6.2.5, fig. 1.

DIAGNOSIS: An elongate, narrow subspecies of *Marginulina prima* with a curved dorsal margin. The oblique ribs fuse on the thickened apertural face forming a series of umbrella-like arches.

STRATIGRAPHICAL RANGE: In Britain, consistent between the *angulata* and *bucklandi* Zone (Copestake and Johnson, 1989). Recorded from the Upper Pliensbachian in Denmark (Nørvang, 1957).

MATERIAL: 32 specimens.

Marginulina prima interrupta (Terquem),

Pl. 7, Fig. 18.

1866a *Marginulina interrupta* Terquem, p. 426, pl. 17, fig. 4a-c.

1936 *Marginulina interrupta* Terquem; Franke, p. 79, pl. 8, fig. 9.

1972 *Marginulina spinata* ssp. *interrupta* Terquem; Norling, p. 80, fig. 43d..

1985 *Marginulina interrupta* Terquem; Riegraf, pl. 9, figs 31-32.

1989 *Marginulina prima interrupta* (Terquem); Copestake and Johnson,
p. 180, pl. 6.2.5, fig. 3.

DIAGNOSIS: A short, parallel-sided subspecies of *Marginulina prima* with ten to 12 ribs, interrupted across the depressed sutures.

REMARKS: The interrupted ribs and nodosarian chamber arrangement make this subspecies of the *M. prima* plexus very distinctive. The test is also broader and less elongate than other members of the plexus.

STRATIGRAPHICAL RANGE: A common member of *tenuicostatum* Zone assemblages with a known British range from *raricostatum* Zone to *tenuicostatum* Zone and an identical European stratigraphic range (Tappan, 1955; Nørvang, 1957; Copestake and Johnson, 1989).

MATERIAL: 2 specimens.

Marginulina prima praerugosa Nørvang,

Pl. 7, Figs 9-12.

1957 *Marginulina prima* subsp. *praerugosa* Nørvang, p. 369, fig. 96.

1876 *Dentalina burgandia* (Terquem); Tate and Blake, p. 461, pl. 18, fig. 29.

1972 *Marginulina prima* ssp. *praerugosa* Nørvang; Norling, p. 76, figs 38a, d, 43b.

1989 *Marginulina prima praerugosa* Nørvang; Copestake and Johnson, p. 182, pl. 6.2.5, fig. 5.

DIAGNOSIS: A subspecies of *Marginulina prima* that has an elongate, straight, parallel sided test with five to six ribs but no thickening on the apertural face. The aperture is marginal.

REMARKS: The form is separated from subspecies *prima* and *rugosa* by the absence of a thickened apertural face and its marginal aperture. It has a shorter straighter test than the subspecies *insignis* and *incisa*. Nørvang (1957) considers *M. prima praerugosa* to be the evolutionary forerunner of subspecies *rugosa*.

STRATIGRAPHICAL RANGE: In Britain this species occurs between the *liascus* Zone to top *tenuicostatum* Zone. European occurrences are restricted to the Hettangian to uppermost Sinemurian (Nørvang, 1957; Norling, 1972; Copestake and Johnson, 1989)

MATERIAL: 78 specimens.

Marginulina prima prima d'Orbigny,

Pl. 7, Figs 3-8.

1849 *Marginulina prima* d'Orbigny, p. 242, no. 262.

1957 *Marginulina prima* subsp. *prima* d'Orbigny; Nørvang, p. 367,

figs 98, 99, 103, 104.

1985 *Marginulina prima* d'Orbigny; Riegraf, pl. 9, figs 23-25.

1989 *Marginulina prima prima* d'Orbigny; Copestake and Johnson, p. 182,

pl. 6.2.5, figs 7, 8.

DIAGNOSIS: A subspecies of *M. prima* that has six to ten longitudinal ribs fusing together as umbrella-like arches on the apertural face. The previous arches are visible between earlier chambers, the sutures are depressed and the aperture eccentric.

REMARKS: The arches on the apertural face are wider and better developed than in subspecies *M. prima rugosa*.

STRATIGRAPHICAL RANGE: In Britain and mainland Europe, this species appears in the Late Pliensbachian and becomes extinct in the Early Toarcian, *falciferum* Zone (Copestake and Johnson, 1989).

MATERIAL: 919 specimens.

Marginulina prima rugosa Bornemann,

Pl. 7, Figs 15-17.

1854 *Marginulina rugosa* Bornemann, p. 39, pl. 3, fig. 26a, b.

1957 *Marginulina prima* subsp. *rugosa* Bornemann; Nørvang, p. 368, fig. 97.

1989 *Marginulina prima rugosa* Bornemann; Copestake and Johnson, p. 182,

pl. 6.2.5, figs 4, 6.

DIAGNOSIS: A subspecies of *Marginulina prima* that has divergent sides with up to 12 ribs fusing on a slightly thickened apertural face. The aperture is marginal while the sutures are indistinct.

REMARKS: The aperture is placed directly on the dorsal edge of the apertural face in *M. prima rugosa* while it is well within the edge in *M. prima prima*; this is the best criterion for classification.

STRATIGRAPHICAL RANGE: First appears in the early Sinemurian becoming extinct in the earliest Toarcian (Copestake and Johnson, 1989).

MATERIAL: 3 specimens.

Genus *Planularia* Defrance, 1826

Planularia inaequistriata (Terquem),

Pl. 2, Figs 3, 7.

1863 *Marginulina inaequistriata* Terquem, p. 191, pl. 8, fig. 15a-f.

1950a *Planularia inaequistriata* (Terquem); Barnard, p. 375, fig. 8c, d, g.

1957 *Planularia inaequistriata* (Terquem); Nørvang, p. 380, figs 148, 149.

1972 *Citharina inaequistriata* (Terquem); Norling, p. 60, figs 29a, b.

1989 *Planularia inaequistriata*; Copestake and Johnson, p. 183, pl. 6.2.5, fig. 16.

DIAGNOSIS: A species of *Planularia* that is ornamented with numerous oblique, irregular ribs. The test occasionally has the later chambers uncoiled and is usually keeled, at least on the lower margin.

STRATIGRAPHICAL RANGE: First appears at the base of the *liascus* Zone in Britain and mainland Europe, disappearing in the *obtusum* Zone (Copestake and Johnson, 1989).

MATERIAL: 237 specimens.

Planularia protracta (Bornemann) gr.

Pl. 2, Fig. 5.

1854 *Cristellaria protracta* Bornemann, p. 39, pl. 4, fig. 27a, b.

1941 *Flabellina centro-gyrata* Macfadyen, p. 58, pl. 4, fig. 58.

1950 *Planularia nucleata* (Terquem); Barnard, p. 376, fig. 8a.

1957 *Falsopalmula* cf. *deslongchampi* Adams, pp. 215-219, text-figs 8-11.

1970 *Flabellinella* sp. Ruget and Sigal, p. 88, pl. 2, figs 9, 10, 13.

1970 *Palmula* sp. Ruget and Sigal, p. 88, pl. 2, figs 11, 12, 14.

1978 *Planularia protracta* (Bornemann) gr.; Copestake, p. 514, pl. 22, figs 1-11.

DIAGNOSIS: A smooth species of *Planularia* composed of up to 12 chambers with early ones slightly coiled and later ones uncoiled. The sutures are strongly oblique and flush or slightly depressed.

STRATIGRAPHICAL RANGE: Rhaetian to Bathonian (Copestake, 1978).

MATERIAL: 156 specimens.

Family POLYMORPHINIDAE d'Orbigny, 1839

Subfamily POLYMORPHININAE d'Orbigny, 1839

Genus *Eoguttulina* Cushman and Ozawa, 1940

Eoguttulina liassica (Strickland),

Pl. 3, Figs 13, 14.

1846 *Polymorphina liassica* Strickland, p. 31, text-fig. b.

1983 *Eoguttulina liassica* (Strickland); Nagy, Løfaldli and Bomstad, p. 120, pl. 2, figs 10-12.

1985 *Eoguttulina liassica* (Strickland); Riegraf, p. 152, pl. 11, figs 29-30.

1989 *Eoguttlina liassica* (Strickland); Copestake and Johnson, pp. 171-2, pl. 6.2.2, fig. 16.

DIAGNOSIS: A variable species of *Eoguttulina* that has a smooth, elongate test with oblique to vertical sutures.

STRATIGRAPHICAL RANGE: Known range Rhaetian to Kimmeridgian (Copestake and Johnson, 1989).

MATERIAL: 138 specimens.

Eoguttulina simplex (Terquem),

Pl. 3, Fig. 15.

1864 *Polymorphina simplex* Terquem, p. 293, pl. 11, figs 1-4.

1985 *Eoguttulina simplex* (Terquem); Riegraf, p. 153, pl. 11, fig. 34.

DIAGNOSIS: A smooth, elongate species of *Eoguttulina*.

REMARKS: This species of *Eoguttulina* is distinguished by its lack of sutures from *E. liassica*.

STRATIGRAPHICAL RANGE: Common in the *tenuicostatum* Zone, the total range is not known (Riegraf, 1985).

MATERIAL: 182 specimens.

Suborder SPIRILLININA Hohenegger and Piller, 1975

Family SPIRILLINIDAE Reuss, 1862

Subfamily SPIRILLININAE Reuss, 1862

Genus *Spirillina* Ehrenburg, 1843

Spirillina infima (Strickland),

Pl. 1, Figs 2, 3.

1846 *Orbis infimus* Strickland, p. 30, text-figure a.

1876 *Cornuspira infima* (Strickland); Blake in Tate and Blake, p. 451, pl. 18, fig. 1.

1952 *Sprillina infima* (Strickland); Barnard, p. 906, figs 1, 2.

1978 *Spirillina infima* (Strickland); Copestake, p. 460, pl. 20, fig. 6.

DIAGNOSIS: A species of *Spirillina* that consists of a globular megalosphere or microsphere around which is planispirally wound a single-chambered tube.

STRATIGRAPHICAL RANGE: *liascus* Zone to uppermost Toarcian (Copestake, 1978).

MATERIAL: 68 specimens.

Suborder **ROBERTININA** Loeblich and Tappan, 1984

Superfamily **CERATOBULIMINACEA** Cushman, 1927

Family **CERATOBULIMINIDAE** Cushman, 1927

Subfamily **REINHOLDELLINAE** Seiglie and Bermúdez, 1965

(Loeblich and Tappan, 1988a)

Genus *Reinholdella* Brotzen, 1948

Reinholdella .(Bartenstein),

Pl. 9, Figs 9-11.

1937 *Discorbis dreheri* Bartenstein; Bartenstein and Brand, p. 192, pl. 6, figs 45a, b; pl. 8, fig. 42a-d; pl. 10, fig. 47a-d.

1952 *Reinholdella dreheri* (Bartenstein); Hofker, p. 20, figs 7–10.

1969 *Reinholdella dreheri* (Bartenstein); Brouwer, p. 43, pl. 7, figs 35, 36.

1972 *Reinholdella dreheri* (Bartenstein); Norling, p. 102, figs 53c, d, 54a.

DIAGNOSIS: A species of *Reinholdella* that has a nearly flat ventral side and a convex dorsal side. Overall the test is almost planoconvex. The sutures are indistinct, not raised or depressed except towards the centre.

STRATIGRAPHICAL RANGE: *liascus* Zone to Lower Bajocian (Norling, 1972).

MATERIAL: 2 specimens.

Reinholdella macfadyeni (Ten Dam) emend. Hofker,

Pl. 9, Figs 6, 7, 8.

1947 *Asterigerina macfadyeni* Ten Dam, p. 396, text-fig. 1a-c.

1952 *Reinholdella macfadyeni* (Ten Dam); Hofker, p. 17, text-figs 3-6.

1969 *Reinholdella macfadyeni* (Ten Dam) emend. Hofker; Brouwer, p. 43, pl. 8, figs 3-7.

1985 *Reinholdella macfadyeni* (Ten Dam); Riegraf, p. 156, pl. 11, figs 44-46.

1989 *Reinholdella macfadyeni* (Ten Dam); Copestake and Johnson, p. 186, pl. 6.2.6, figs 15, 17.

DIAGNOSIS: A species of *Reinholdella* that has a convex dorsal surface with raised, merging spiral and septal sutures. The ventral surface is smooth, planar/slightly convex with an umbilical plug.

STRATIGRAPHICAL RANGE: Earliest British record is Upper Pliensbachian of Yorkshire (Copestake and Johnson, 1989), ranging to the Lower Aalenian in Europe (Brouwer, 1969)

MATERIAL: 859 specimens.

Reinholdella pachyderma Hofker,

Pl. 9, Figs 4, 5.

1952 *Reinholdella pachyderma*, Hofker, pp. 15, 16, text figs 1, 2.

1969 *Reinholdella pachyderma* Hofker; Brouwer, p. 43, pl. 7, figs 1, 2.

1981 *Reinholdella pachyderma* subsp A; Copestake and Johnson, p. 102, pl. 6.1.5, figs 10, 11.

1985 *Reinholdella pachyderma* Hofker; Riegraf, p. 156, pl. 11, figs 48, 49.

DIAGNOSIS: A species of *Reinholdella* that has a low trochospiral test which can be variable in shape and planar on the ventral side with a partially open umbilicus.

STRATIGRAPHICAL RANGE: Copestake and Johnson (1981) give a British range from *raricostatum* Zone to late *jamesoni* Zone. In Europe this range is extended to include *spinatum* and *tenuicostatum* Zones (Riegraf, 1985).

MATERIAL: 589 specimens.

Reinholdella? planiconvexa (Fuchs),

Pl. 9, Figs 1–8.

1969 ?*Conorboides* sp.; Brouwer, p. 42, pl. 7, figs 31, 32.

1970 *Oberhauserella planiconvexa* Fuchs, p.113, pl. 9, fig. 7.

1977 *Conorboides* sp. 1 Horton and Coleman, pl. 2, figs 13, 14.

1997 *Oberhauserella quadrilobata* Fuchs; BouDagher-Fadel *et al.*, pl. 2.2, figs 4, 7, 9.

1989 *Reinholdella? planiconvexa* (Fuchs); Copestake and Johnson, p. 187,
pl. 6.2.6, figs 11, 16.

1990 *Conorboides* sp. Muller, p. 190, pl. 6, figs 27, 28.

DIAGNOSIS: A species of *Reinholdella* that has a smooth discoidal to ovate test which is plano-convex in section. It has a marked umbilical hollow, two to 2.5 whorls with fix to six chambers in the final whorl.

REMARKS: The questionable generic allocation arises from the lack of toothplate (Copestake and Johnson, 1989), but this species does posses the two apertures that are characteristic of *Reinholdella*. Occurring in high abundance in the *falciferum* Zone at Tilton, this species was noted from the same zone by Horton and Coleman (1977) as *Conorboides* sp. More recently specimens have been described from the Toarcian (*falciferum* Zone) of the Swiss Alps (Simmons *et al.,* 1997) which are referred to *Oberhauserella quadrilobata* Fuchs. *Oberhauserella* is an aragonitic benthic member of the Robertinina and thought to be morphologically transitional to *Conoglobigerina*, a meroplanktonic foraminifera.

The small test size of the specimens collected is also distinctive:

Dimensions	Ventral height x width	Length of final chamber
fig. 1	160 x 150μm	70μm
fig. 2	154 x 179μm	105μm
fig. 6	136 x 160μm	92μm
fig. 7.	147 x 174μm	104μm
fig. 8	166 x 174μm	105μm

STRATIGRAPHICAL RANGE: Copestake and Johnson (1989) give a British range of Rhaetian to *jamesoni* Zone. In mainland Europe, the species is abundant in the Hettangian to Lower Sinemurian (Brouwer, 1969). This study extends the known range up to the *falciferum* Zone.

MATERIAL: 1270 specimens.

Suborder **ROTALIINA** Delage and Hérouard, 1896

Superfamily **BOLIVINACEA** Glaessner, 1937

Family **BOLIVINIDAE** Glaessner, 1937

Classification after Loeblich and Tappan, 1988a.

Genus *Brizalina* O.G. Costa, 1856

Brizalina liassica Terquem, 1858,

Pl. 9, Fig. 3.

1858 *Textilaria liasica* Terquem, p. 74, pl. 4, fig. 12a, b.

1936 *Bolivina rhumbleri* n. sp.; Franke, p. 126, pl. 12, fig. 21.

1937 *Bolivina rhumbleri amalthea* n. subsp. (Brand); Bartenstein & Brand, p.185, pl. 7, fig. 1 a-i.

1989 *Brizalina liassica* (Terquem); Copestake & Johnson, p. 187, pl. 6.2.6, figs 20, 21.

DIAGNOSIS: A smooth compressed species of *Brizalina* with an elongate slit as an aperture. Early sutures are flush, later ones depressed.

REMARKS: This is the only known Lower Jurassic species of *Brizalina.*

STRATIGRAPHICAL RANGE: Consistent British range from *jamesoni* Zone to top *tenuicostatum* Zone (Copestake and Johnson, 1989). Reported to range into the Aalenian by Norling, (1972).

MATERIAL: 610 individuals.

Chapter 4 Foraminiferal Distribution

4.1 Key features of the faunas

Of the 304 species and subspecies of Lower Jurassic foraminifera from the Mochras Borehole, described by Johnson (1975) and Copestake (1978), 71 have been recovered and identified during this study comprising 23 genera from 11 families and 6 suborders. The 301 samples analysed from the Lower Jurassic of north-west Europe include an expanded Hettangian - Sinemurian boundary section, an Upper Sinemurian to Lower Pliensbachian section and sections that cover the range of lithologies developed during the Upper Pliensbachian to Upper Toarcian interval. Lithologies from the latter interval are notoriously difficult to prepare for microfossils (Lord, 1974; Riegraf, 1985; Muller, 1990) especially where black shale or ironstone facies are developed. This is reflected in the high proportion of samples that proved to be barren or did not succumb sufficiently to the disaggregation techniques available (Appendix A). However, the faunas recovered from the fossiliferous samples provide useful and valuable information about the foraminiferal response to the Early Toarcian events while, by means of a consistent taxonomy, allow a detailed comparison of the British assemblages with continental European foraminiferal faunas.

In general the faunas recovered are smaller benthic calcareous foraminifera (group A of Gordon, 1970) which are characteristic of the Boreal realm during the Early Jurassic (Copestake and Johnson, 1989). These normal marine shelf assemblages are dominated by nodosariids, with fewer numbers of Miliolina, Robertinidae, Spirillinina, Involutina, Buliminacea, Textulariina, Polymorphinidae and Cassidulinacea. Occasionally the subordinate groups become dominant over nodosariids. For example, the Robertinidae, represented by the genus *Reinholdella*, dominate in the *exaratum* Subzone, *falciferum* Zone at Tilton while *Reinholdella macfadyeni* is abundant in the *tenuicostatum* Zone of the North Yorkshire Coast.

The faunas recovered from all the sections studied also include many forms which are considered to be important for zonation and correlation purposes in the British and European Lower Jurassic (Copestake and Johnson, 1989). These index foraminifera are useful in that they provide independent verification for the ammonite zonation schemes applied to the sections.

The localities from which data are available are listed below with foraminiferal range charts correlated with the stratigraphical columns for each section. Attention is drawn to the key features of the faunas. Where the subzone only is referred to, the corresponding zone can be determined from Figure 11.

4.1.1 South Dorset Coast

The large residues from the Down Cliff Sands (DCS1-7) consist of fine quartz sand with varying amounts of white mica flakes. Foraminifera are very scarce, probably due to leaching out of the calcareous component by ground waters. Many picking trays of sediments were scanned per sample and in the case of samples DCS6 and 7 a low number of poorly preserved foraminifera were recovered. These individuals showed signs of corrosion and/or dissolution. However, even with the low number of individuals recovered, the diversity was still quite high with 8 species and subspecies being represented (Figure 20).

In sample BB1, there was for the first time, a relatively large calcareous residue containing many foraminifera. This assemblage is dominated by *Lingulina tenera* plex. *pupa*.

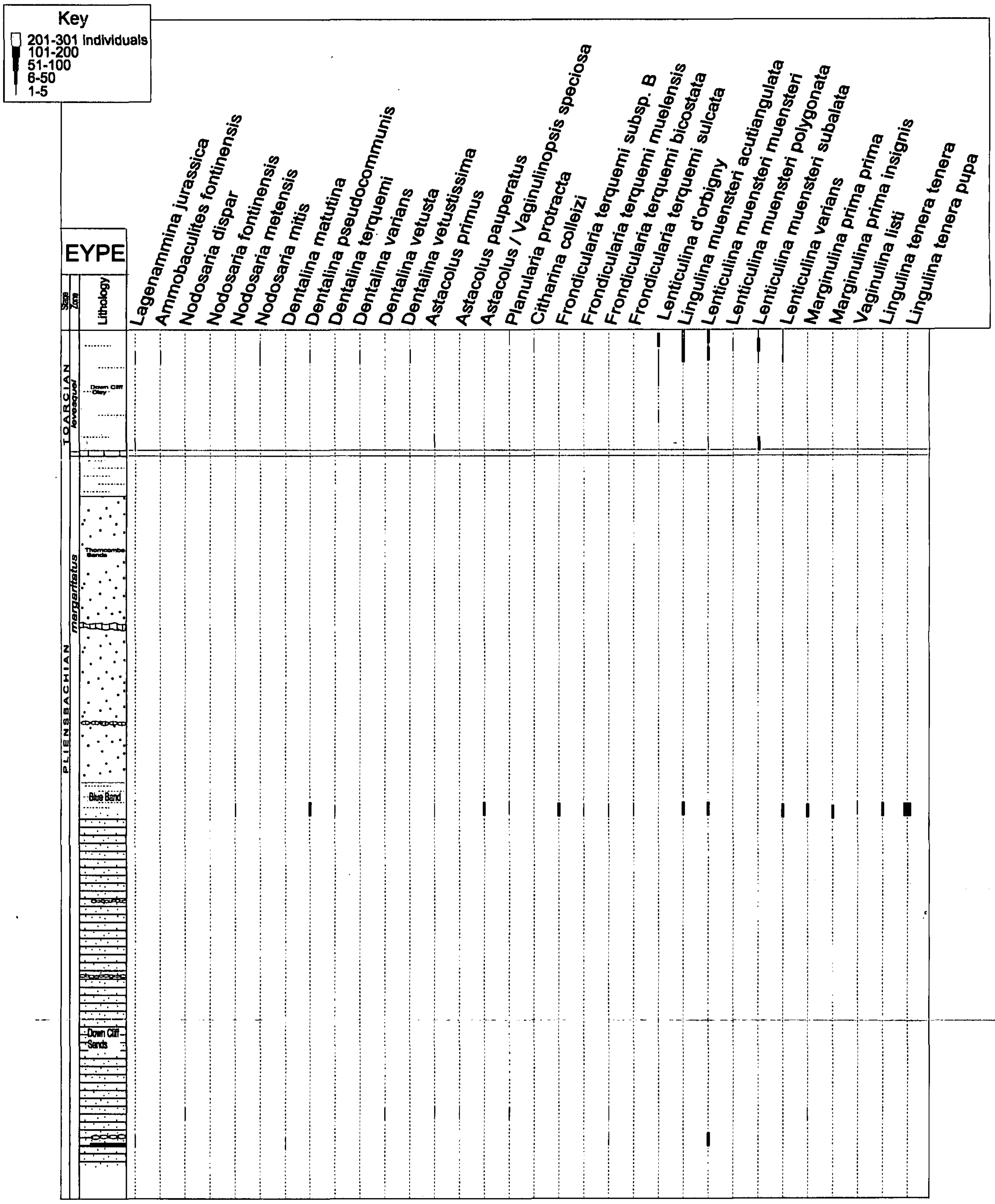


Figure 20. Stratigraphic distribution of foraminifera in the Pliensbachian to Toarcian of Eype, south Dorset Coast. See Fig. 12 for key to lithologies and sample details.

Samples from the Thornecombe Sands (THS1-2) shows a return to large, quartz sand dominated residues with scarce, poorly preserved foraminifera.

Above the Junction Bed, the residues from samples DC1-10 are very large and again consist of angular quartz sand with a high proportion of white mica flakes.

The foraminiferal assemblages from the Down Cliff Clay, DC1-10 (*levesquei* Zone), at Eype show a return to greater diversity and a larger test size, indicative of more normal oxygenated conditions. These assemblages are dominated by the *Lenticulina muensteri* plexus group and *Marginulina* spp.

The presence of *Lenticulina d'Orbigny* in these samples is stratigraphically significant. At Mochras this distinctive species first appears close to the top of the *crassum* Subzone, *bifrons* Zone, and has an identical first appearance at Ilminster in Somerset (Boomer *et al.*, in prep).

4.1.2 Leicestershire

The stratigraphical distribution of foraminifera recovered from Tilton Railway Cutting and Brown's Hill Quarry is illustrated in Figure 21. Twenty-four species and subspecies were identified from these sections which yield typical Pliensbachian – Toarcian assemblages.

margaritatus Zone

In common with the other mid-Pliensbachian sections in this study, the assemblages display a reasonable diversity of smaller calcareous foraminifera. The *Lingulina tenera* plexus is represented by large numbers of the subspecies A, *tenera* and *pupa*. The *Marginulina prima* plexus, *Lenticulina muensteri muensteri* and *Lenticulina varians* are also major components of these assemblages.

spinatum – tenuicostatum Zones

The Upper Pliensbachian to Lower Toarcian interval at both Tilton and Brown's Hill Quarry is represented by the oolitic ironstone facies of the Marlstone Rockbed. This facies is not suitable for micropalaeontological preparation and yields little microfauna. Samples from this interval were examined in thin-section but failed to reveal the presence of any microfauna including foraminifera.

exaratum Subzone

At the base of the *exaratum* Subzone, at Tilton there is an abundance of very small (~100μm diameter) trochospiral foraminifera that have been tentatively identified as *Reinholdella? planiconvexa*. This species has also been reported from the *falciferum* Zone of the Upper Lias at Empingham (Rutland) by Horton & Coleman, (1977). Given their extremely low abundance before the Toarcian events and their 'bloom' once the environmental conditions markedly declined, this taxon can be considered a *disaster* or *opportunist* species as described by Harries *et al.*, (1996). The species dominates after the rapid transgression in the *exaratum* Subzone before the onset of low oxygen conditions.

The 'paper shales', or most bituminous facies, of the *exaratum* Subzone yield no foraminifera. However, the fauna returns immediately after the return to less organic rich mudstones. *Reinholdella? planiconvexa* dominates these assemblages while *Lenticulina varians* and associated species contribute low numbers to the assemblages.

falciferum Subzone

The recovery of foraminiferal faunas from the Toarcian anoxic events begins to take place during the *falciferum* Subzone. Members of the coiled *Lenticulina* and *Astacolus* genera

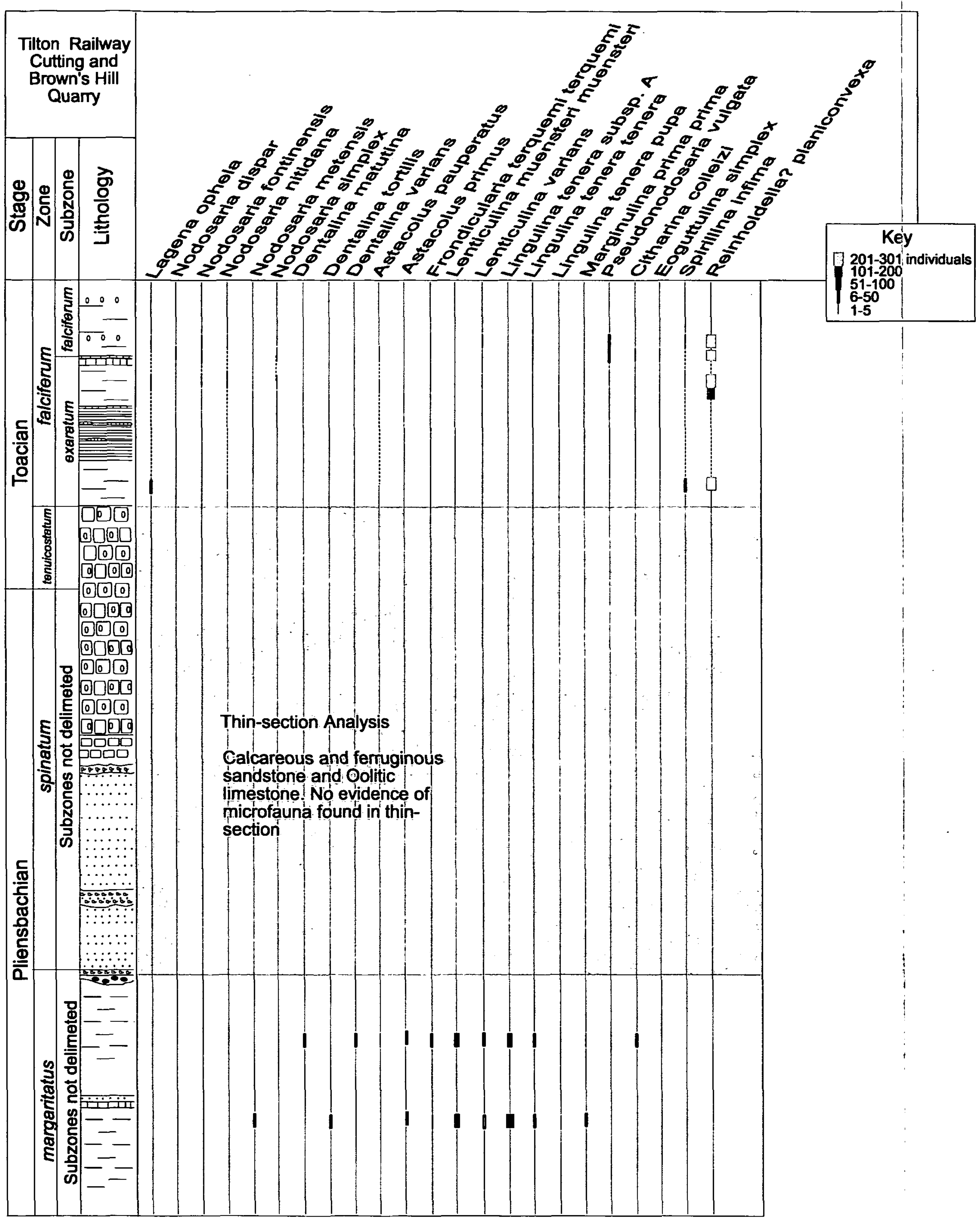


Figure 21. Stratigraphical distribution of foraminifera in the Upper Pliensbachian to Lower Toarcian of the Tilton area, Leicestershire. See Figs 13a & b for key to lithologies and sample details.

appear at Tilton in low diversity late *falciferum* Subzone assemblages. *Reinholdella? planiconvexa* continues to dominate these increasingly diverse assemblages which also sees the appearance of *Pseudonodosaria vulgata, Nodosaria fontinensis, N. dispar* and *Eoguttulina simplex* at Tilton. These assemblages are typically Toarcian in character, lacking members of the *Lingulina tenera* and *Marginulina prima* plexus groups which became extinct during the *exaratum* Subzone anoxic events.

4.1.3 North Yorkshire Coast

spinatum Zone

The Cleveland Ironstone Formation proved to be a difficult lithology to prepare for microfossils. However the samples examined from around the Pliensbachian - Toarcian boundary did yield foraminiferal assemblages, illustrated in Figure 22. The assemblages are typically Lower Jurassic in character, dominated by the long-ranging *Lingulina tenera* plex. *tenera, Lingulina tenera* plex. *pupa*, *Marginulina prima* plex. *prima*, and *Pseudonodosaria vulgata* with a minor component of *Dentalina* and some arenaceous species including *Thurammina jurensis* and *Trochammina sablei.*

At Mochras, where this zone is represented by argillaceous sediments, it is marked by an influx of *Opthalmidium* and *Spirillina*. The North Yorkshire Coast assemblages have a greater affinity with those described from Ilminster, Somerset (Boomer *et al.*, in prep) which are also almost entirely composed of members of the Suborder Lagenina. The predominant genera present at Ilminster are *Lenticulina*, *Planularia* and *Citharina.*

tenuicostatum Zone

The composition of the foraminiferal assemblages changes in the Grey Shales Member of the Whitby Mudstone Formation. Different species are introduced which dominate in this lower part of the Toarcian. *Brizalina liassica* and *Reinholdella macfadyeni* occur in abundance in the *tenuicostatum* zone of the North Yorkshire Coast. As indicators of deep water and transgressive events (Brouwer, 1969), *R. macfadyeni* disappears with the onset of low-oxygen conditions in the Jet Rock. A regional variation is seen within the *Reinholdella* populations, which increase in abundance in the *tenuicostatum* Zone; in eastern and central England and the southern North Sea Basin, *Reinholdella macfadyeni* attained maximum abundance from the base of the zone, whilst in the Celtic Sea Basin (Mochras Borehole), *R. dreheri* and *R. pachyderma* dominated the assemblages (Copestake and Johnson, 1989).

Towards the top of the Grey Shales Member (*semicelatum* Subzone) the assemblages experience an decrease in diversity while the dominance of *Brizalina liassica*, *Reinholdella macfadyeni* and *Reinholdella pachyderma* increases to the near exclusion of the other species.

falciferum Zone

The samples from the Mulgrave Shale Member did not yield any microfauna after presenting difficult problems with the disaggregation of such highly organic mudrocks. These shales also displayed varying degrees of lamination (See Chapter 5) which were examined in thin-section. This analysis provided an independent validation of the lack of benthic activity during this highly anoxic period.

This zone sees the last occurrences of several taxa: the *Frondicularia terquemi, Lingulina tenera* and *Marginulina prima* plexus groups underwent major declines while several sub-species became extinct.

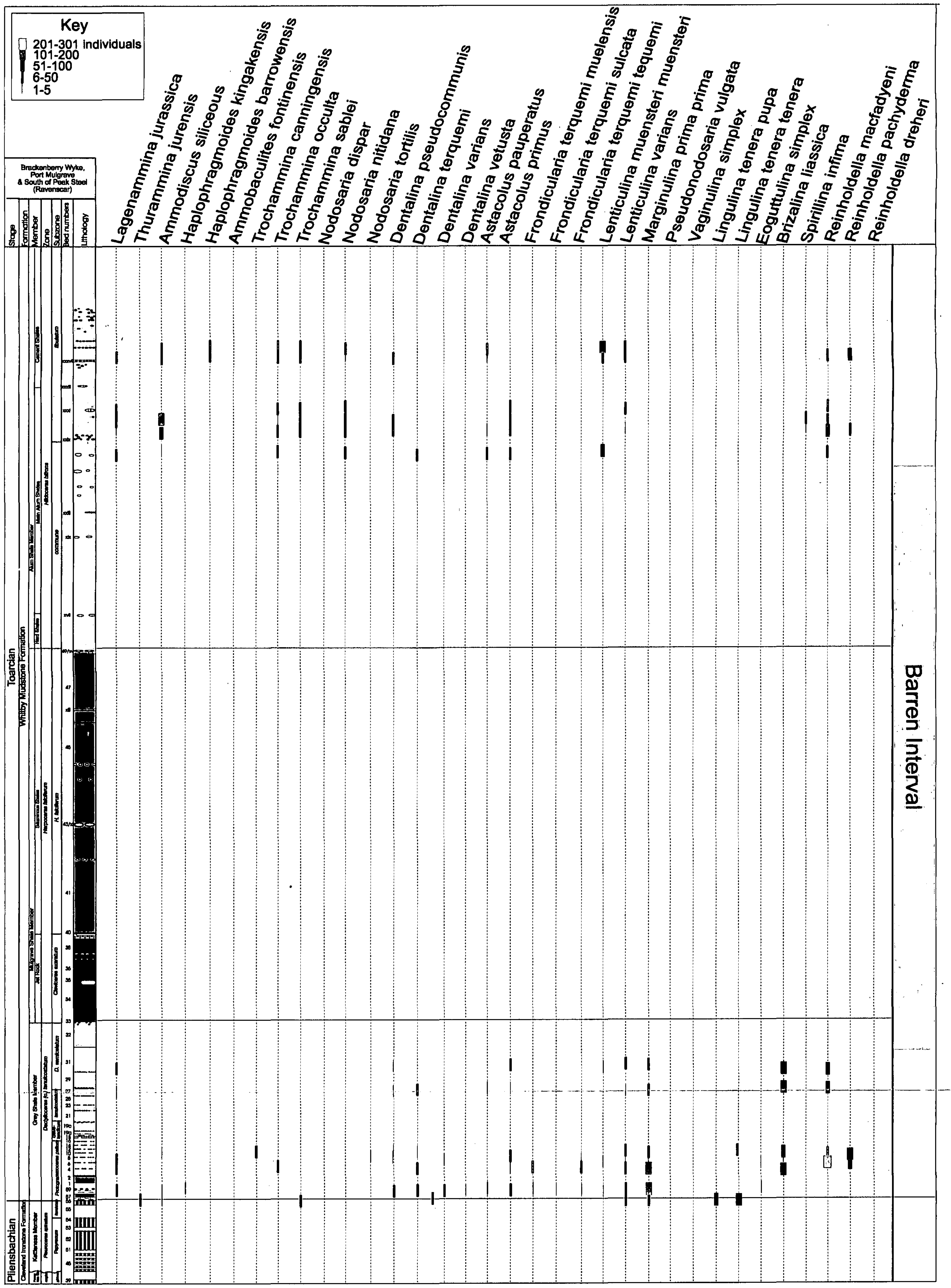


Figure 22. Stratigraphic distribution of the foraminifera in the Pliensbachian - Toarcian of the North Yorkshire Coast. See Fig. 11 for key to lithologies and sample details.
Barren intervals have been confirmed by examination of the samples in thin-section. The presence of varying degrees of lamination, high organic content and no evidence of microfauna defines the barren samples. See Chapter 5 for further details.

commune Subzone

The lower part of the Alum Shales Member also proved to be barren of microfauna. However, the samples located towards the top of the *commune* Subzone yielded a reasonably diverse foraminiferal fauna dominated by *Lenticulina muensteri muensteri* with associated *Lagenammina jurassica*, *Trochammina occulta*, *Nodosaria nitidana* and *Astacolus pauperatus*.

fibulatum Subzone

During this Subzone the foraminiferal assemblages continue to increase in abundance and diversity and contain a high proportion of *Lenticulina muensteri muensteri* and *Reinholdella pachyderma*. Many of the species that dominated Pliensbachian and earlier assemblages such as the *Lingulina tenera* and *Marginulina prima* plexus groups are missing. However many taxa survived extinction and became important constituents of Toarcian, and later on, Middle Jurassic assemblages.

4.1.4 South Central France

The 30 samples analysed from Truc de Balduc yielded 44 species and subspecies from the Upper Pliensbachian to Upper Toarcian interval, as illustrated in Figure 23.

As discussed earlier, *spinatum* Zone foraminifera are not well known from Britain owing to the unfavourable condensed ironstone facies. The Shales between the thin ironstones of the North Yorkshire Coast (Cleveland Ironstone Formation) are characterised by a predominantly arenaceous foraminiferal association, probably indicative of reduced sea-floor oxygenation. In the only other known British argillaceous successions of this zone, the Mochras Borehole (Copestake and Johnson, 1989) and Ilminster (Boomer *et al.*, in prep) calcareous foraminifera are predominant, with nodosariids in the lower part and

Spirillina spp. and *Opthalmidium* spp. becoming common in the upper part in the case of the Mochras borehole or dominated by members of the Lagenina at Ilminster.

The *spinatum* Zone assemblages at Truc de Balduc show similarities with both of the British examples. The characteristic presence of miliolid taxa such as *Opthalmidium liascum* and *O. macfadyeni* associated with *Spirillina infima* combines at Truc in an abundant and diverse assemblage with members of the lagenids such as *Lingulina tenera* plex. *tenera* and *Lenticulina muensteri muensteri.*

The *tenuicostatum* Zone at Truc de Balduc is mostly absent and is only represented by a greatly reduced *semicelatum* Subzone. This feature gives the impression of a considerable extinction level across the Pliensbachian - Toarcian boundary, but it is not possible to determine the rate of any extinctions during this interval owing to the lack of sediments. However, samples through the *semicelatum* and *exaratum* Subzones exhibit a greatly decreased diversity and the loss of many species from the Upper Pliensbachian assemblages. This interval is populated by members of the *Lenticulina muensteri* and *Lenticulina varians* plexus groups and characterised by the appearance of *Brizalina liassica* and *Eoguttulina liassica.*

By the onset of anoxia in the *falciferum* Zone the samples prove to be barren of any microfauna and display the characteristic lamination of these black shales. The recovery of the foraminiferal fauna commences in the *commune* Subzone of the *bifrons* Zone with the dominance of *Lenticulina muensteri muensteri* and other members of the plexus. *Reinholdella macfadyeni* and *Eoguttulina liassica* are important contributors to these assemblages.

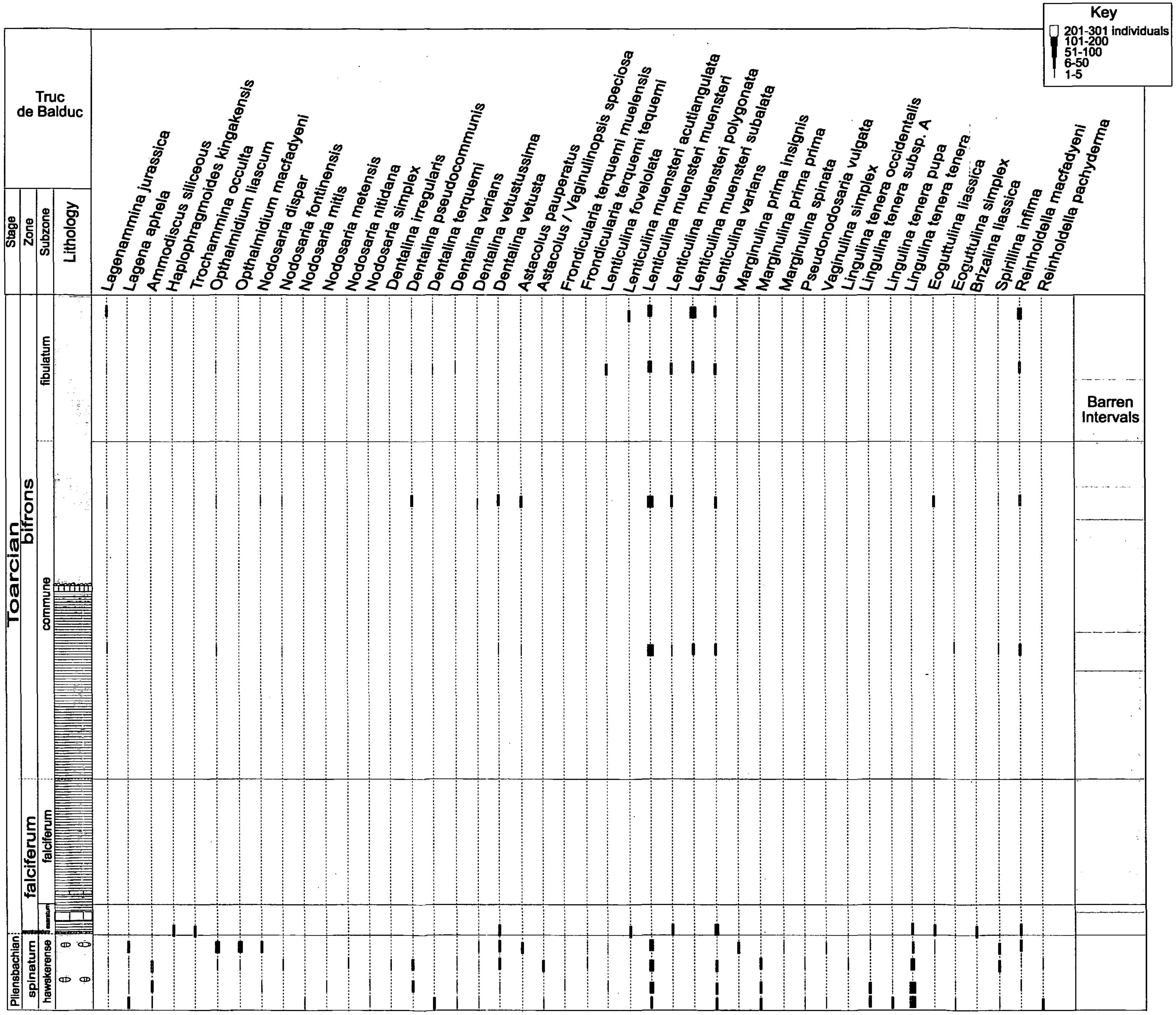


Figure 23. Stratigraphical distribution of foraminifera in the Upper Pliensbachian to Upper Toarcian of the Truc de Balduc, S. France. See Fig. 15 for key to lithologies and sample details.

Samples which yielded no foraminifera were confirmed as barren by thin-section examination. The barren facies consisted of organic-rich, micro-laminations with no evidence for the presence of a micro-fauna. See Chapter 5 for further details.

During the *bifrons* Zone, the oxygenation levels appear to fluctuate causing periods of stagnation in the basin and a consequent lack of foraminiferal faunas. While the faunas continue to recover during this zone, they never reach the same levels of diversity or abundance seen during the Late Pliensbachian. The continuing presence of *Reinholdella macfadyeni* and *Brizalina liassica* in the assemblages could be interpreted as a result of the lowered oxygen conditions or the continuance of a transgressive phase.

These *bifrons* Zone assemblages differ from those of the other sections studied, especially in the retention of *Reinholdella* and *Brizalina* although a similar pattern was reported from the Mochras Borehole (Copestake and Johnson, 1989) where deep marine conditions persisted throughout the Late Toarcian.

4.1.5 South-west Germany

Assemblages from the Dotternhausen quarries show a decrease in abundance across the Pliensbachian - Toarcian boundary with few extinctions (this study; Riegraf, 1985). The main extinction level occurs in the *semicelatum* Subzone of the *tenuicostatum* Zone with some species persisting into the middle of the *falciferum* Zone. Early *tenuicostatum* Zone assemblages are dominated by *Lenticulina* and *Marginulina* with a minor *Nodosaria* component (Figure 24).

This locality lacks the common marker occurrences usually seen in the *tenuicostatum* Zone of an increase in abundance of *Reinholdella* spp. and *Brizalina liassica*. The normally ubiquitous *Lingulina tenera* plexus is reduced to only one representative, *Lingulina tenera* plex. *tenera* while members of the *Marginulina prima* plexus group predominate.

The development of anaerobic conditions reflected in the Posidonienschiefer (*falciferum* Zone) results in an absence of all benthic foraminifera. The *falciferum* Zone at Dotternhausen is greatly expanded and includes two extra Subzones: *elegantulum and elegans*. This interval is entirely barren of any microfauna which does not recover until the *commune* Subzone of the *bifrons* Zone. In common with other *bifrons* Zone assemblages, the Dotternhausen faunas are low diversity dominated by *Reinholdella macfadyeni* and *Lenticulina muensteri muensteri* with a minor arenaceous component of *Trochammina occulta* and *T. topagorukensis*. The diversity does not truly attain pre-*falciferum* Zone levels until the top of the *bifrons* Zone, along with the macrofauna (Little, 1996).

4.1.6 East Quantoxhead

The majority of the residues proved to be barren of any microfauna with 12 samples containing foraminifera, illustrated in Figure 25. The fossiliferous samples, however, contain an abundant and diverse foraminiferal fauna. Also present were ostracods, echinoid spines and micro-gastropods.

The predominance of calcareous foraminifera, and especially the *Lingulina tenera* plexus group, is typical of Lower Jurassic sequences in Northern Europe and the United Kingdom. The assemblages also comprise useful index species and other forms diagnostic of the Lower Jurassic and the Hettangian - Sinemurian in particular. The first and last appearances of *Lingulina tenera* plex. *substriata* are restricted to the top of the Hettangian *angulata* zone and are therefore useful for correlating the base of the Sinemurian (Copestake and Johnson, 1989). The consistent appearance of *Planularia inaequistriata* and the *Frondicularia terquemi* plexus group above the boundary at East Quantoxhead is also a characteristic of the basal Sinemurian zones. Copestake and Johnson (1984) also include the important index species *Lingulina tenera* plex. *substriata*, *Planularia inaequistriata* and *Dentalina matutina* in their benthic foraminiferal zonation scheme. This scheme, of international applicability for both southern and northern hemispheres, covers Britain and seventeen other countries and regions throughout the world.

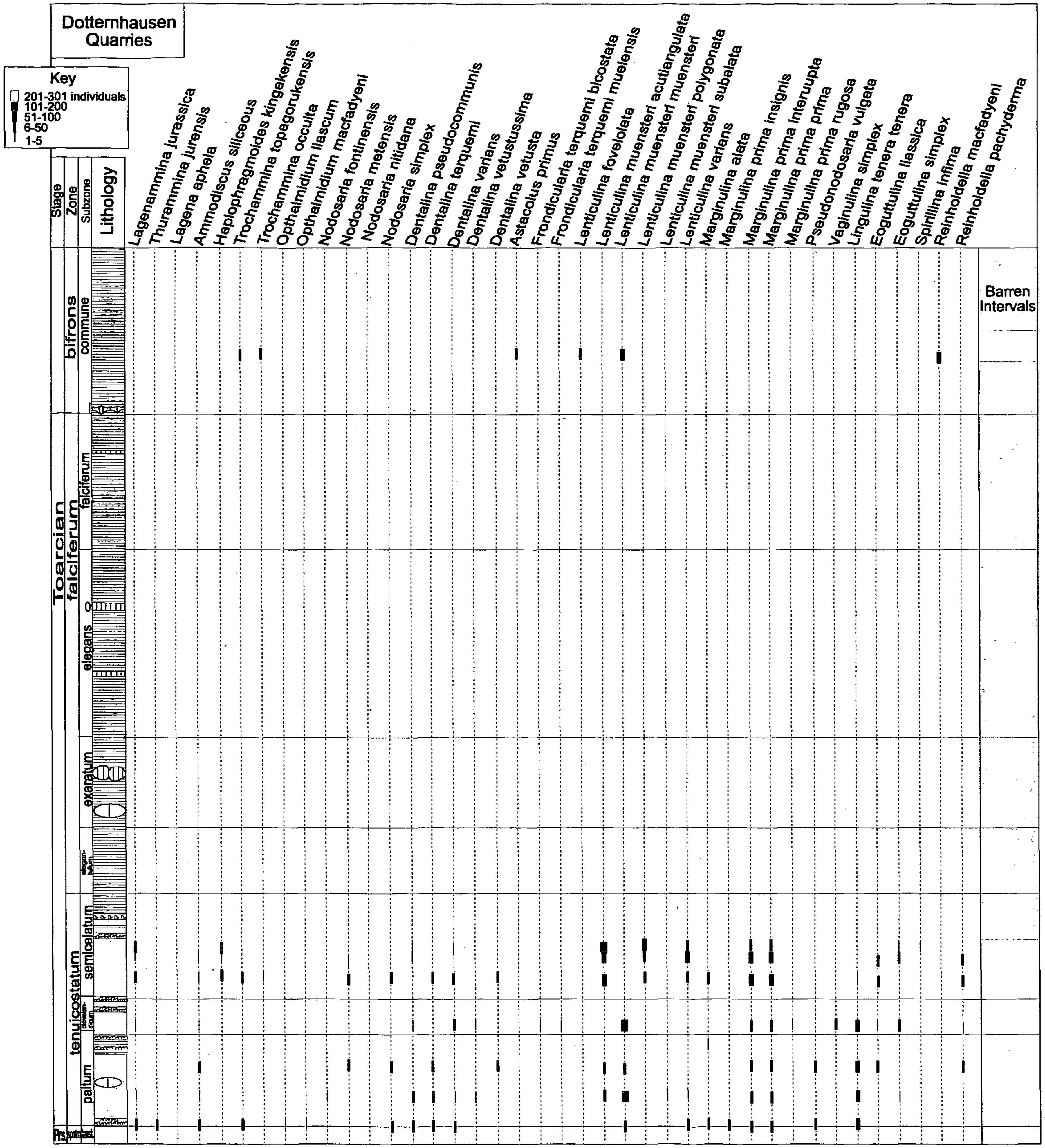


Figure 24. Stratigraphic distribution of the foraminifera in the Pliensbachian - Toarcian of the Dotternhausen Quarries, south-west Germany. See Fig. 16 for key to lithologies and sample details.
Barren intervals have been confirmed by examination of the samples in thin-section. The presence of varying degrees of lamination, high organic content and no evidence of microfauna defines the barren samples. See Chapter 5 for further details.

The foraminiferal assemblages at East Quantoxhead, and those of the Lower Jurassic in general, are characterised by combinations of a restricted number of species which constitute the bulk of the fauna. These smaller benthic foraminifera occur in assemblages dominated by certain forms: the elongate, flattened *Astacolus* and the uniserial, ribbed groups of *Lingulina tenera*, *Frondicularia* and *Marginulina*. Also present are a number of species of the long ranging genera *Lenticulina* and *Nodosaria*. These species can be considered as the main components of the assemblages.

The predominance of the *Lingulina tenera* (Bornemann) plexus with associated *Lenticulina* and *Marginulina* species in the lower part of the section suggests inner to near shelf environments with periods of normal oxygen levels.

Towards the boundary, there is a noticeable decline in abundance and diversity, eventually resulting in the extinction of *Lingulina tenera* plex. *substriata*. Indicative of a regressive phase, Copestake and Johnson (1989) also report that several index foraminifera become extinct at or near the top of the *angulata* Zone at many European localities (*Lingulina tenera collenoti*, *L. tenera substriata*, *Frondicularia terquemi* subsp. A) while *Dentalina langi* both appears and becomes extinct within the late *angulata* Zone. An increase in diversity across the boundary indicates a return to deeper, oxygenated conditions, reflecting a transgressive event.

The ostracod fauna of this section was investigated by Hart and Hylton (1999) with the aim of determining the correlation potential of this group as part of the proposal for a Global Stratotype Section and Point (Page *et al.*, 2000).

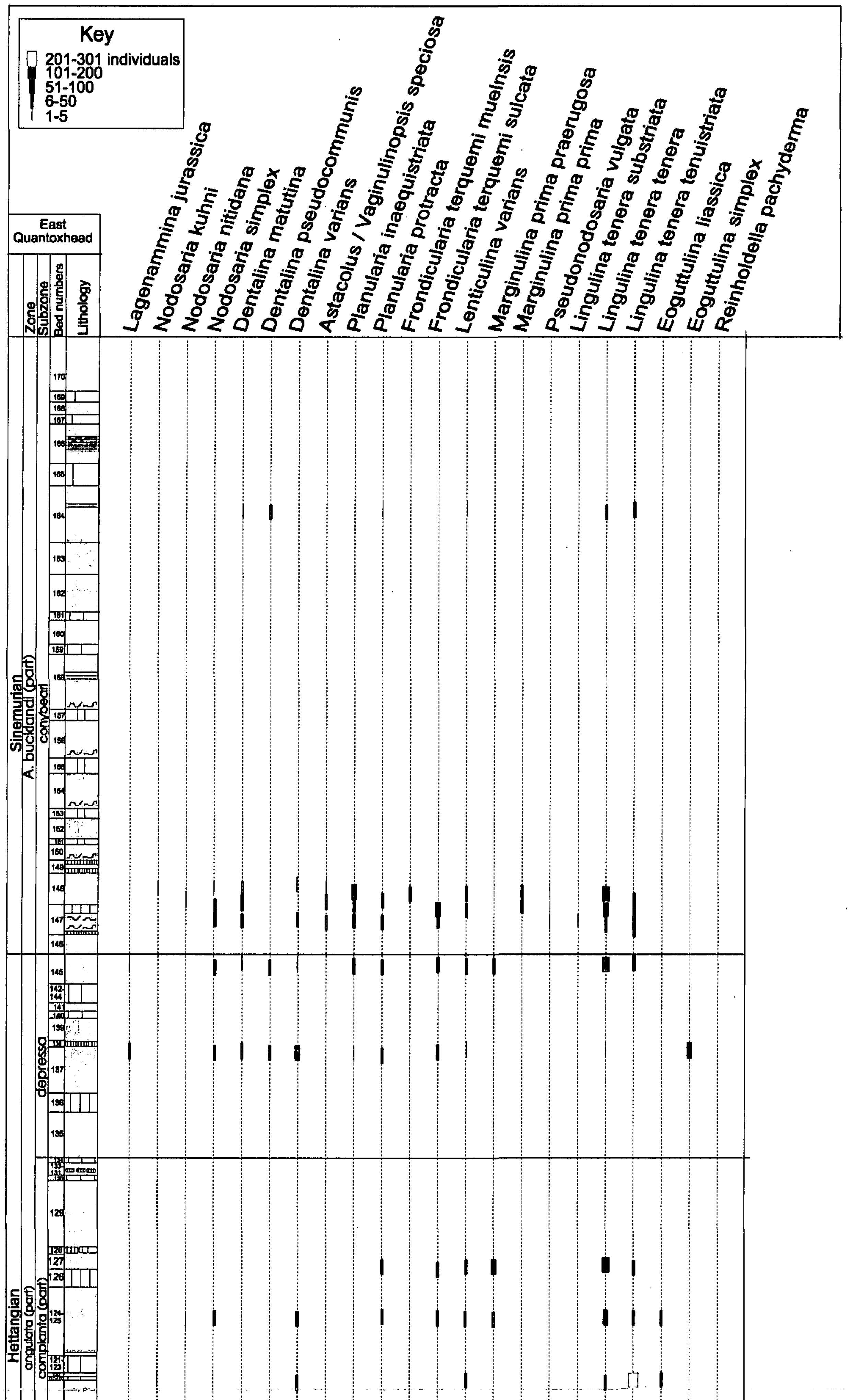


Figure 25. Stratigraphic distribution of the foraminifera in the Hettangian - Sinemurian of East Quantoxhead, West Somerset. See Fig 17 for key to lithologies and sample details.

4.1.7 Robin Hood's Bay

The majority of samples collected from this locality either proved to be resistant to any of the disagregation techniques employed or did not yield any microfauna. The latter situation was particularly evident in the samples from the Pyritous Shales which did not contain any foraminifera. Four of the 34 samples processed, from around the top of the Sinemurian *aplanatum* Subzone (Figure 26), contained an abundant and reasonably diverse microfauna. The consistent appearance of *Dentalina matutina* is diagnostic of the Sinemurian - Pliensbachian boundary (Copestake and Johnson, 1989) while the first appearance of *Frondicularia terquemi muelensis* is seen at the base of the *raricostatum* Zone in the British Jurassic.

The long-ranging, characteristic members of Lower Jurassic foraminiferal assemblages are also present at this locality: *Lingulina tenera tenera, Lingulina tenera tenuistriata, Lenticulina muensteri muensteri* and *Marginulina prima prima* indicating normal marine conditions and connections with the other basins during this period.

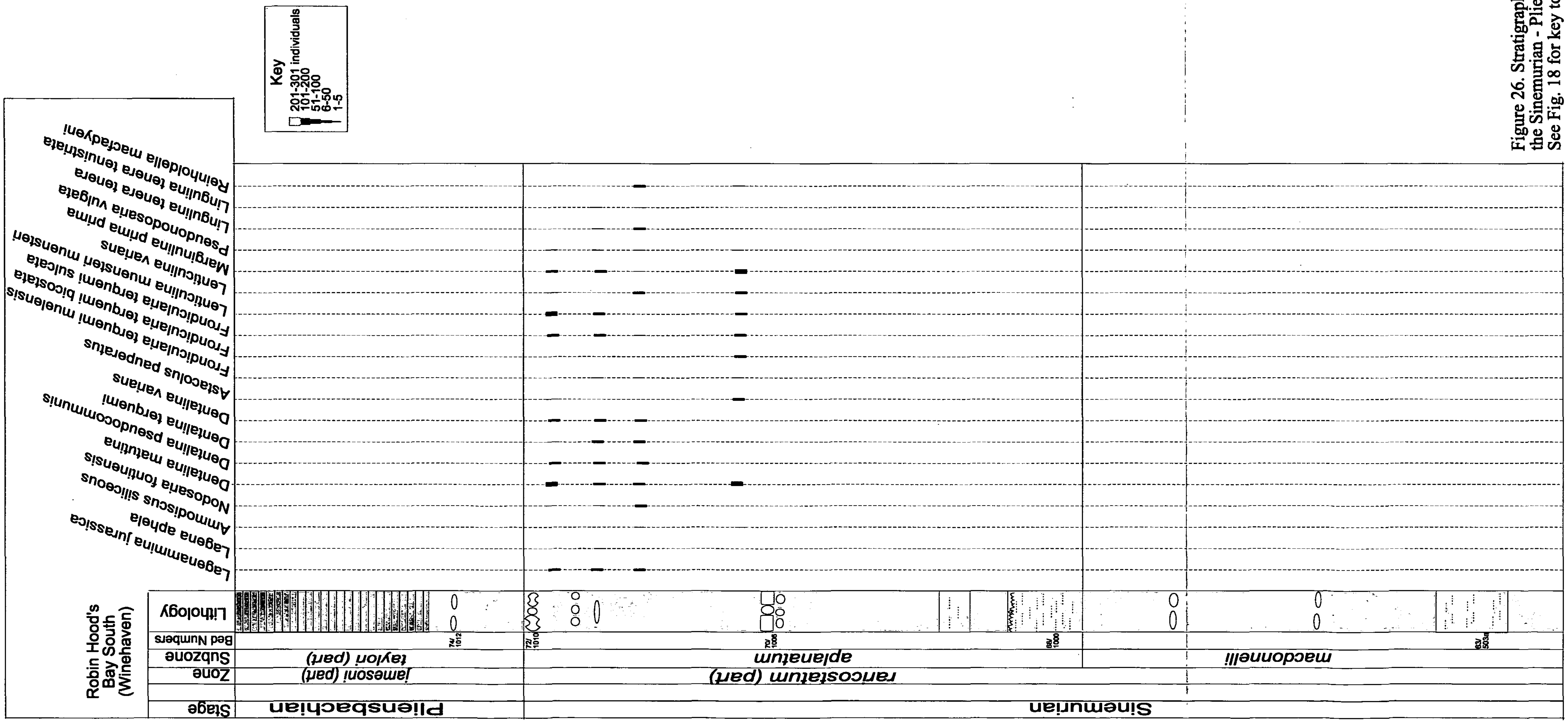


Figure 26. Stratigraphic distribution of foraminifera in the Sinemurian - Pliensbachian of Robin Hood's Bay. See Fig. 18 for key to lithologies and sample details.

4.2 Overview of the faunas recovered

4.2.1 North west European Distribution

The distribution of the 71 species recovered during this study is summarised in Tables 4 and 5, giving their occurrences in the seven localities studied across north west Europe along with their zonal distribution in the Lower Jurassic (Hettangian to Toarcian). Species are listed in taxonomic order, following that given in Chapter 3.

Species	DC	LE	NY	SF	SG	EQ	RB
Lagenammina jurassica (Barnard)	●		●	●	●	●	●
Thurammina jurensis (Franke)			●		●		
Ammodiscus siliceus (Terquem)			●	●	●		●
Haplophragmoides barrowensis Tappan			●				
Haplophragmoides kingakensis Tappan			●	●	●		
Ammobaculites fontinensis (Terquem)	●		●				
Trochammina canningensis Tappan			●				
Trochammina occulta (Bach)			●	●	●		
Trochammina sablei Tappan			●				
Trochammina topagorukensis Tappan					●		
Opthalmidum liascum (Kübler and Zwingli)				●	●		
Opthalmidum macfadyeni Wood and Barnard				●	●		
Frondicularia terquemi bicostata d'Orbigny	●				●		●
Frondicularia terquemi muelensis Ruget and Sigal	●		●	●	●	●	●
Frondicularia terquemi subsp. B. Copestake and Johnson	●						
Frondicularia terquemi sulcata Bornemann	●		●			●	●
Frondicularia terquemi terquemi d'Orbigny		●	●	●			
Lingulina tenera plex. *collenoti* (Terquem)						●	
Lingulina tenera plex. *occidentalis* (Berthelin)				●			
Lingulina tenera plex. *pupa* (Terquem)	●	●	●	●			
Lingulina tenera plex. *substriata* (Nørvang)						●	
Lingulina tenera plex. *tenera* (Bornemann)	●	●	●	●	●	●	●
Lingulina tenera plex. *tenuistriata* (Nørvang)						●	●
Lingulina tenera plex. subsp. A (Copestake and Johnson)		●		●			
Nodosaria dispar Franke	●	●	●	●			
Nodosaria fontinensis Terquem	●	●		●	●		●
Nodosaria kuhni Franke						●	
Nodosaria metensis Terquem	●	●		●	●		
Nodosaria mitis (Terquem and Berthelin)	●			●			
Nodosaria nitidana Brand		●	●	●	●	●	
Nodosaria simplex (Terquem)		●		●	●	●	
Pseudonodosaria vulgata (Bornemann)		●	●	●	●	●	●
Lagena aphela Tappan		●		●	●		●
Citharina colliezi (Terquem)	●	●					
Dentalina irregularis Terquem				●			
Dentalina matutina d'Orbigny	●	●				●	●
Dentalina vetustissima d'Orbigny	●			●	●		
Dentalina pseudocommunis Franke	●		●	●	●	●	●
Dentalina terquemi d'Orbigny	●		●	●	●		●
Dentalina tortilis Franke		●	●				

Species	DC	LE	NY	SF	SG	EQ	RB
Dentalina varians Terquem	●	●	●	●	●	●	●
Dentalina vetusta d'Orbigny	●		●	●	●		
Vaginulina listi (Bornemann)	●						
Vaginulina simplex Terquem			●	●	●		
Astacolus / Vaginulinopsis speciosa (Terquem)	●			●		●	
Astacolus pauperatus (Jones and Parker)	●	●	●	●			●
Astacolus pediacus Tappan						●	
Astacolus primus d'Orbigny	●	●	●		●		
Lenticulina d'Orbigny Roemer	●						
Lenticulina foveolata (Franke)				●	●		
Lenticulina muensteri muensteri (Roemer)	●	●	●	●	●		●
Lenticulina muensteri acutiangulata (Terquem)	●			●	●		
Lenticulina muensteri polygonata (Franke)	●			●	●		
Lenticulina muensteri subalata (Reuss)	●			●	●		
Lenticulina varians (Bornemann) plexus	●	●	●	●	●	●	●
Marginulina alata Terquem					●		
Marginulina prima insignis (Franke)	●			●	●		
Marginulina prima interrupta (Terquem)					●		
Marginulina prima praerugosa Nørvang						●	
Marginulina prima prima d'Orbigny	●	●	●	●	●	●	●
Marginulina prima rugosa Bornemann					●		
Planularia inaequistriata (Terquem)						●	
Planularia protracta (Bornemann) gr.	●					●	
Eoguttulina liassica (Strickland)				●	●	●	
Eoguttulina simplex (Terquem)		●	●	●	●	●	
Spirillina infima (Strickland)		●	●	●	●		
Reinholdella dreheri (Bartenstein)			●				
Reinholdella macfadyeni (Ten Dam) emend. Hofker			●	●	●	●	●
Reinholdella pachyderma Hofker			●	●	●		
Reinholdella? planiconvexa (Fuchs)		●					
Brizalina liassica Terquem			●	●			

Table 4. Geographic distribution of foraminiferal species occurrences across all studied sections: SD - South Dorset Coast; LE - Leicestershire; NY - North Yorkshire Coast; SF - Southern France; SG - South-West Germany; RB - Robin Hood's Bay; EQ - East Quantoxhead.

The following conclusions regarding the species distribution can be drawn from the data in Table 4:

a. The following 9 Species:

Lagenammina jurassica
Frondicularia terquemi muelensis
Lingulina tenera tenera
Pseudonodosaria vulgata
Dentalina pseudocommunis
Dentalina varians

Lenticulina muensteri muensteri
Lenticulina varians
Marginulina prima

are common to all the localities. Apart from having a wide geographic distribution they also occur throughout the Lower Jurassic and provide the background elements of the majority of assemblages.

b. The following 16 species are less widespread:

Ammodiscus siliceous
Frondicularia terquemi sulcata
Lingulina tenera pupa
Nodosaria dispar
Nodosaria metensis
Nodosaria nitidana
Lagena aphela
Dentalina matutina
Dentalina terquemi
Dentalina vetusta
Astacolus pauperatus
Astacolus primus
Eoguttulina simplex
Spirillina infima
Reinholdella macfadyeni
Reinholdella pachyderma

and occur in 4 of the localities.

c. The following 32 species have a very restricted geographical distribution:

Thurammina jurensis
Haplophragmoides barrowensis
Ammobaculites fontinensis
Trochammina canningensis
Trochammina occulta

Trochammina sablei
Trochammina topagorukensis
Opthalmidium liascum
Opthalmidium macfadyeni
Frondicularia terquemi subsp. B
Lingulina tenera occidentalis
Lingulina tenera substriata
Lingulina tenera tenuistriata
Lingulina tenera subsp. A
Nodosaria kuhni
Nodosaria kuhni
Nodosaria mitis
Citharina colliezi
Dentalina irregularis
Dentalina tortilis
Vaginulina listi
Lenticulina d'Orbigny
Lenticulina foveolata
Marginulina alata
Marginulina prima interrupta
Marginulina prima praerugosa
Marginulina prima rugosa
Planularia inaequistriata
Planularia protracta
Reinholdella dreheri
Reinholdella? planiconvexa
Brizalina liassica

The zonal ranges of the foraminiferal species are detailed in Table 5, These data are a composite of all occurrences from the seven sections studied. The data are supplemented with additional information on first and last occurrences from the following sources:

- Copestake and Johnson, 1989;
- Copestake, 1975;

- Johnson, 1970;
- Riegraf, 1985; and
- Nørvang, 1957.

Species	a	b	r	j	m	sp	te	f	bi	v	th	l
Lagenammina jurassica (Barnard)	●		●		●	●	●		●			●
Thurammina jurensis (Franke)						O	●					
Ammodiscus siliceus (Terquem)	O		●			●	●		●			
Haplophragmoides barrowensis Tappan									●			
Haplophragmoides kingakensis Tappan							●	●				
Ammobaculites fontinensis (Terquem)												●
Trochammina canningensis Tappan	O						●					
Trochammina occulta (Bach)							●	●	●			
Trochammina sablei Tappan							●		●			
Trochammina topagorukensis Tappan						●	●		●			
Opthalmidum liascum (Kübler and Zwingli)						●	●		●			
Opthalmidum macfadyeni Wood and Barnard	O					●	⊗					
Frondicularia terquemi bicostata d'Orbigny			●		●		⊗					
Frondicularia terquemi muelensis Ruget and Sigal		●	●		●	●	⊗					
Frondicularia terquemi subsp. B. Copestake and Johnson					O		⊗					
Frondicularia terquemi sulcata Bornemann	O	●	●				⊗					
Frondicularia terquemi terquemi d'Orbigny	O				●	●	⊗					
Lingulina tenera plex. *collenoti* (Terquem)	⊗											
Lingulina tenera plex. *occidentalis* (Berthelin, 1879)			O			⊗						
Lingulina tenera plex. *pupa* (Terquem)	O				●	●	●					
Lingulina tenera plex. *substriata* (Nørvang)		⊗										
Lingulina tenera plex. *tenera* (Bornemann)	●	●	●		●	●	●	⊗				
Lingulina tenera plex. *tenuistriata* (Nørvang)	●	●	●									
Lingulina tenera plex. subsp. A (Copestake and Johnson)					O	●						
Nodosaria dispar Franke					●	●		●	●			
Nodosaria fontinensis Terquem			●			●	●	●				
Nodosaria kuhni Franke	●	●										
Nodosaria metensis Terquem					●	●	●					
Nodosaria mitis (Terquem and Berthelin)						●						●
Nodosaria nitidana Brand	●	●				●		●	●			
Nodosaria simplex (Terquem)	●	●				●	●	⊗				
Pseudonodosaria vulgata (Bornemann)		●	●			●	●	●				
Lagena aphela Tappan			●			●		●				
Citharina colliezi (Terquem)					O			●				●
Dentalina irregularis Terquem						●						
Dentalina matutina d'Orbigny	●	●	●		⊗							
Dentalina vetustissima d'Orbigny						●	●		●			●
Dentalina pseudocommunis Franke	●	●	●		●	●	●		●			●
Dentalina terquemi d'Orbigny	O		●		●	●	●		⊗			
Dentalina tortilis Franke							●					
Dentalina varians Terquem	●	●	●		●	●	●					●
Dentalina vetusta d'Orbigny					●	●	●	●	●			
Vaginulina listi (Bornemann)					●							
Vaginulina simplex Terquem						●	●					
Astacolus / Vaginulinopsis speciosa (Terquem)	O	●			●	●						
Astacolus pauperatus (Jones and Parker)			●		●	●	●	●	●			
Astacolus pediacus Tappan	●											
Astacolus primus d'Orbigny					●		●		●			●

Species	a	b	r	j	m	sp	te	f	bi	v	th	l
Lenticulina d'Orbigny Roemer												●
Lenticulina foveolata (Franke)						●	●		●			
Lenticulina muensteri muensteri (Roemer)			●		●	●	●		●			●
Lenticulina muensteri acutiangulata (Terquem)					●	●	●	●	●			●
Lenticulina muensteri polygonata (Franke)							●	●	●			●
Lenticulina muensteri subalata (Reuss)							●		●			●
Lenticulina varians (Bornemann) plexus	●	●	●		●	●	●	●	●			●
Marginulina alata Terquem						●	●					
Marginulina prima insignis (Franke)	O				●	●	●					
Marginulina prima interrupta (Terquem)			O			●	⊗					
Marginulina prima praerugosa Nørvang	●											
Marginulina prima prima d'Orbigny		●	●		●	●	⊗					
Marginulina prima rugosa Bornemann			O				⊗					
Planularia inaequistriata (Terquem)	●	⊗										
Planularia protracta (Bornemann) gr.					●							●
Eoguttulina liassica (Strickland)	●					●	●	●	●			
Eoguttulina simplex (Terquem)	●					●	●	●	●			
Spirillina infima (Strickland)						●	●	●	●			
Reinholdella dreheri (Bartenstein)												
Reinholdella macfadyeni (Ten Dam) emend. Hofker			●			●	●	●	●			
Reinholdella pachyderma Hofker	●					●	●		●			
Reinholdella? planiconvexa (Fuchs)								●				
Brizalina liassica Terquem				O		●	●	●				

Table 5. North-West European Zonal ranges of foraminiferal species recovered during this study: a - angulata; b - bucklandi; r - raricostatum; j - jamesoni; m - margaritatus; sp - spinatum; te - tenuicostatum; f - falciferum; bi - bifrons; v - variabilis; th - thouarsense; l - levesquei Zones. ● - occurrence of species; O- first occurrence of species; ⊗ - last occurrence of species. The *exaratum* Subzone event horizon is indicated by the shaded column.

4.2.2 Pre-event assemblages

In order to make some useful comparisons of assemblages during and after the Oceanic Anoxic Event, the Hettangian - Pliensbachian faunas of East Quantoxhead and Robin Hood's Bay were studied. Indeed if extinctions are usually to be expected at times of regression, it is notable that several index foraminifera become extinct at or near the top of the *angulata* Zone: e.g., *Lingulina tenera substriata* (Hylton, 1999; Copestake and Johnson, 1989). The notable features of the background faunas of this interval are:

- Early Jurassic in character
- High diversity and abundance

The foraminiferal faunas recovered from the Lower Jurassic sections at East Quantoxhead and Robin Hood's Bay are typical, diverse assemblages characteristic of the smaller benthonic assemblages of the Boreal realm. The faunas are dominated by the *Lingulina tenera* Bornemann plexus group with associated nodosariids and a minor component of the *Frondicularia terquemi* Bornemann plexus group. The consistent appearance of *Planularia inaequistriata* and the *Frondicularia terquemi* plexus group above the boundary at East Quantoxhead is also a characteristic of the basal Sinemurian zones.

4.2.3 Event assemblages

The main development of the Oceanic Anoxic Event of Jenkyns (1988) is during the *falciferum* Zone but in considering the characteristics of the *event* assemblages, those distinguishing features of assemblages in the preceding *tenuicostatum* Zone are also included. Thus the salient features of the event assemblages are:

- the elimination of certain groups;
- a tendency towards smaller size;
- lowered diversity; and
- the appearance of opportunist or disaster taxa.

A fundamental turnover in the foraminiferal assemblages occurs during the Toarcian *falciferum* Zone during which many taxa became extinct. Uniserial forms such as species of *Nodosaria*, *Frondicularia* and *Lingulina tenera* which dominated Pliensbachian faunas become extinct at this level.

A further noticeable trend in foraminifera from low oxygen conditions is towards a reduction in test size. Comparison with Hettangian - Sinemurian assemblages from the UK comprising large *Lenticulina*, *Lingulina tenera*, *Nodosaria* and *Marginulina* species (Hylton, 1998) shows a decrease in test size of these genera by the early Toarcian. Having a small test may also maximise relative surface area (Bernhard, 1986).

At the base of the *exaratum* Subzone, *falciferum* Zone at Tilton, there is a significant abundance of very small (~100μm diameter) *Reinholdella? planiconvexa*. This occurrence bears similarities to a reported abundance of the aragonite genus *Conorboides* from the *falciferum* Zone of the Upper Lias at Empingham, Rutland (Horton & Coleman, 1977). Given their extremely low abundance before the Toarcian events and their 'bloom' once the environmental conditions markedly decline this, taxon could be described as a *disaster* or *opportunist* species (Harries *et. al.*, 1996). The species dominates after a rapid transgression in the *exaratum* Subzone before the onset of low oxygen conditions.

Similarly, *Reinholdella macfadyeni* occurs in maximum abundance in the *tenuicostatum* Zone of the North Yorkshire Coast. As an indicator of deep water and transgressive events (Brouwer, 1969), *R. macfadyeni* also disappears with the onset of low-oxygen conditions in the Jet Rock.

4.2.4 Recovery assemblages

The post-oceanic anoxic event faunas (Late Toarcian) are generally characterised by being:

- dominated by the *Lenticulina* genus especially *L. muensteri muensteri*;
- of low but increasing diversity; and
- indicative of future development into typically Middle Jurassic assemblages

The recovery of foraminiferal faunas from the Toarcian anoxic events begins to take place during the *falciferum* Subzone, *falciferum* Zone. Members of the coiled *Lenticulina* and *Astacolus* genera appear at Tilton in low diversity late *falciferum* Subzone assemblages, while by *levesquei* Zone times at Eype, the assemblages have returned to pre-event diversity levels and are dominated by *Lenticulina* indicating outer shelf, oxygenated conditions.

The foraminiferal assemblages from the Down Cliff Clay (*levesquei* Zone) at Eype show a return to greater diversity and a larger test size, indicative of more normal oxygenated conditions. These assemblages are dominated by the *Lenticulina muensteri* plexus group and *Marginulina*.

4.3 Summary

A fundamental turnover in the foraminiferal assemblage occurs in the *falciferum* Zone during which many foraminiferal taxa become extinct. While large scale benthic foraminiferal trends have been previously identified (Brouwer, 1969; Copestake and Johnson, 1989; Brasier, 1988), this high resolution study has revealed the existence of opportunist or disaster foraminiferal species. These species are found during times of environmental stress and exploit available habitat space for short periods of time.

Sea-level rise across the Pliensbachian - Toarcian boundary culminated in the *falciferum* Zone of the Toarcian and is one of the best authenticated eustatic events in the Jurassic. This major transgressive pulse was marked by deeper water marine sequences and was associated with the deposition of organic-rich shales.

The development of anoxia coincides with a notable period of mass extinction of the marine fauna. High resolution sampling and study of the microfaunas through several sequences in the United Kingdom confirm that benthic foraminiferal faunas were similarly affected by an early Toarcian *falciferum* Zone event. Samples were analysed from Pliensbachian - Toarcian mudstone, clay and shale sequences of the South Dorset Coast, the Midlands and the Yorkshire Coast. The sections studied show distinct changes in assemblages across the Pliensbachian - Toarcian boundary and in the basal zones of the Toarcian.

Evidence for a foraminiferal extinction event in the Pliensbachian - Toarcian includes the elimination of the important early Jurassic *Lingulina tenera, Frondicularia terquemi* and *Marginulina prima* plexus groups, initiating a significant period of turnover of the microfauna. A marked change also occurred in the character of associated nodosariid assemblages: the uniserial forms of *Nodosaria, Frondicularia* and *Lingulina*, dominating the Pliensbachian assemblages, were largely replaced by coiled *Lenticulina* in the early Toarcian. A reduction in test size and a decline in species diversity, compared with Hettangian to Sinemurian foraminiferal assemblages, reflect the development of low oxygen conditions followed by a subsequent renewal of the microfauna in the Middle Toarcian.

Global Stratotype Sections and Points (GSSPs)

This study has also contributed useful data towards the assessment of two Global Stratotype Sections and Points for two stages of the Lower Jurassic (Hylton, 1998; Hart & Hylton, 1999; Hylton, 1999; Page *et al.*, 2000):

- The ranges of identified foraminiferal taxa at East Quantoxhead have been extended and provide further data to assist in the definition of the base of the Sinemurian stage.
- The foraminiferal faunas at Robin Hood's Bay have been investigated. The consistent appearance of *Dentalina matutina* is diagnostic of the Sinemurian - Pliensbachian

boundary (Copestake and Johnson, 1989) while the first appearance of *Frondicularia terquemi muelensis* is seen at the base of the *raricostatum* Zone in the British Jurassic. The long-ranging, characteristic members of Lower Jurassic foraminiferal assemblages are also present at this locality: *Lingulina tenera tenera, Lingulina tenera tenuistriata, Lenticulina muensteri muensteri* and *Marginulina prima prima.*

The only other alternative to Robin Hood's Bay is the Bosso River section near Cagli in Italy. This is a totally limestone succession which, because of work on the ammonite biostratigraphy, remains a useful reference for the Mediterranean Province. However, the Sinemurian-Pliensbachian boundary can not be observed owing to slumps and a fault which hides the contact between the latest Sinemurian beds and the Pliensbachian sequence (Meister, 1999).

Chapter 5 Microfacies Analyses

5.1 Introduction

Sequences of organic-rich, laminated mudrocks deposited under oxygen-deficient conditions commonly contain interbedded, bioturbated intervals that are thought to reflect periodic episodes of improved bottom-water oxygenation (Savrda and Bottjer, 1989). Some of the most recent advances in the understanding of marine benthic environments of ancient epicontinental seas have been in the study of fluctuations of oxygen content on, or close to, the sea bed (Tyson and Pearson, 1991; Oschmann, 1993; Wignall, 1994; Allison *et al.*, 1995). A broad survey of British Jurassic black shales biofacies led Wignall and Hallam (1991) to propose a new classification of six oxygen-restricted bio-facies, four of them dysaerobic and two anaerobic. Their accompanying lithofacies classification ranging from shelly shale to shelly laminite and barren laminite, was based on Hallam (1987).

The Posidonienschiefer has also been the subject of an interesting controversy concerning the thickness of the anoxic water layer above the sediment-water interface. Kauffman (1978, 1981) challenged the conventional wisdom that these black shales were deposited in waters that were anoxic for a considerable distance above the sediment-water interface -a *euxinic* environment. He argued that large ammonites, that settled on the sea bed after death, would protrude above a very thin anoxic zone, of only a few centimetres thick; evidenced by large numbers of pteriomorph bivalves which had attached themselves byssally to these so-called 'benthic-islands'. On the basis of a variety of palaeoecological and taphonomic observations Kauffman argued for an environment of fluctuating weakly to moderately oxygenated benthic environments and only episodic, short-term anoxic events.

Seilacher (1982a, b) has contested this interpretation and expressed support for the conventional stagnant basin model for the Posidonienscheifer on the grounds of his own palaeoecological and taphonomic observations. For him the pteriomorph bivalves were attached byssally to swimming or floating ammonites, together with some cementing forms, in a manner analogous to the inoceramids and planktonic crinoids that are associated with driftwood and which, eventually, settle on to an anoxic sea bed. Only occasionally was the anoxic regime disturbed by short-lived high energy events, probably storms, which were experienced on the basin floor. Only in a few cases, more in the areas marginal to the basin, were these events strong or persistent enough to allow low-diversity benthic communities to invade the muddy bottoms as short-lived post-event faunas.

While the black shales of the Jet Rock seem with conform well to Seilacher's stagnant basin model (Wignall and Hallam, 1991) Kauffman's alternative model, which implies that frequent oscillations could have taken place between facies of different degrees of bottom oxygenation, has received support from a multi-disciplinary study of the Posidonienschiefer. Recent geochemical, palaeoecological and sedimentological investigation of the black shales of the Dotternhausen quarries has revealed evidence for fluctuations of the redox boundary and hence oxygen availability in the benthic environment (Oschmann *et al.,* 1999; Röhl, 1998; Schmid-Röhl *et al.*, 1999). The detailed data were used to reconstruct an approximate oxygenation curve throughout the Posidonienschiefer section (Figure 27). The discovery of thin bioturbated horizons within the laminated sediments would seem to indicate brief periods of oxygenation. Further evidence for Kaufman's 'benthic islands' comes from the presence of ammonites encrusted

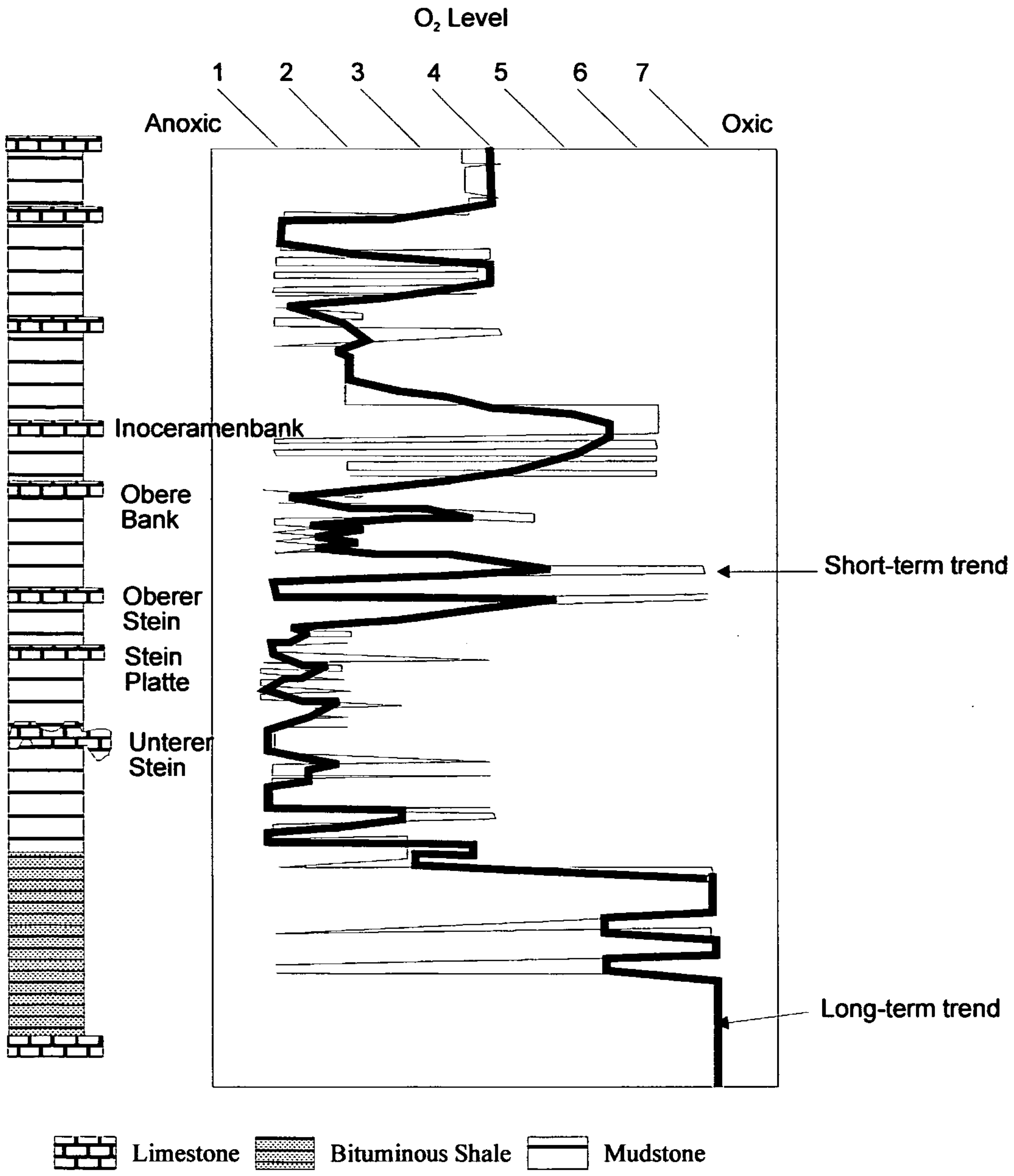


Figure 27. Reconstruction of an approximate oxygen curve through the Posidonienscheifer. The short-term trend curve reflects short term fluctuations of the redox boundary. The overlying curve shows the long term trend. After Schmid-Röhl et al. (1999).

with bivalves and serpulids. Occurrences of juvenile bivalves points to failed benthic colonisation events during very short episodes of bottom water oxygenation, particularly between the limestone marker beds Oberer Stein and Unterer Stein (see Figure 24). Schmid-Röhl *et al.,* (1999) show that by plotting the sulphur content of a range of samples against their TOC (Total organic carbon) and considering the benthic faunal content, the fluctuations in the redox boundary can be seen. In the case of horizons with abundant tiny juvenile shells, the Carbon/Sulphur (C/S) plots point to continuously anoxic bottom water conditions with free H_2S. Conversely. C/S plots of samples derived from the Inoceramenbank, rich in *Pseudomytiloides dubius* shells, show that the organic carbon and sulphur content is relatively low in this part of the section. C/S plots of samples completely free of benthic fauna show that the redox boundary was situated somewhere in the water column and hence excluded benthic life. Although there have been discrepancies between geochemical and palaeoecological indices of anoxia, a number of recent studies (e.g., Brumsack, 1991; Hild and Brumsack, 1998; Bellanca *et al.*, 1999) have highlighted the usefulness of trace element geochemistry in identifying subtle environmental changes in mudrock dominated sequences. Additionally, owing to the nature of an extinction event, a high proportion of the samples analysed during this study proved to be barren of any benthic microfauna.

In order to extract as much palaeoenvironmental information as possible from the sample sets in this study, a second investigative approach was taken. This approach involved systematically characterising the microfacies that were encountered in the various shale units. Allied with this methodology was trace element analysis of a suite of samples from the upper Pliensbachian to Toarcian successions of Brackenberry Wyke and south of Peak Steel on the north Yorkshire coast. It was the purpose of this study to determine the depositional settings of Lower Toarcian sediments from Yorkshire, Dotternhausen and

Truc de Balduc. Thin section and backscattered electron microscopy (BSEM) observations were employed to assess litho- and biofacies distribution. Coupled with high resolution geochemical data, this study aimed to assess the significance and formation of the prevalent sedimentary laminations and to provide insights into:

- the presence or absence of benthic microfauna in samples that could not be disaggregated using available techniques;
- palaeoenvironmental data where foraminiferal evidence is lacking; and
- the relationship between trace elements, the development of anoxic conditions and changes in sea-level during these intervals.

This work was initially conceived, and greatly supported, by Dr G. D. Price (University of Plymouth) who provided the background and expertise for the geochemical analysis of the Yorkshire Coast samples while Mr R. Bowers must be thanked for performing the ICP analysis. The thin-section and BSEM analyses of the Yorkshire Coast samples were undertaken jointly with Dr Price while the conclusions for Yorkshire, Dotternhausen and Truc de Balduc were the results of combined discussion and interpretation. Dr J. Macquaker (University of Manchester) aided with the identification of an intriguing microfacies.

5.2 Methods

All the samples collected during this study were subjected to the processing methods detailed in Section 2.3.1 in order to determine their microfossil content. As would be expected from an extinction event, many of the samples proved to be barren of any microfauna. Many of the more bituminous samples also proved difficult to disaggregate with the available methods. Subsequently, a representative suite of samples were selected from the Dotternhausen and Truc de Balduc sections for thin-section and BSEM analysis only. More detailed sampling was undertaken of the uppermost section of the Cleveland Ironstone Formation and the Whitby Mudstone Formation (Figure 14) of the Yorkshire Coast. Freshly exposed, subsurface, material was obtained whilst avoiding calcite-rich concretionary layers. Samples for thin sectioning were orientated in the field and 40 were made into polished thin sections for optical work.

For BSEM analysis (using a JEOL 6100 scanning electron microscope with an Oxford Instruments Link systems backscattered electron detector and quantitative Link x-ray microanalytical system) the polished thin sections were coated with carbon.

In addition, a series of thin-sections were selected from those samples that contained an abundant microfauna to provide a control against which the rest of the thin-sections could be judged. Forty oriented shale samples collected at Brackenberry Wyke, Port Mulgrave and Ravenscar through the Grey Shales, Jet Rock *s. s.* and Bituminous Shales, twenty-nine non-oriented samples from Truc de Balduc and thirty-seven from Dotternhausen were studied.

As noted above, trace element geochemistry has proved useful in the identification of subtle environmental changes in mudrock dominated sequences. Hence, a suite of trace elements (Mn, Ca, Sr, Mg, Fe, and Al) have been analysed for using 0.400-0.500 g samples by Inductively Coupled Plasma (ICP) spectrometry analysis on a Perkin Elmer 3000. When sub-sampling, macrofossils were avoided. Each mudrock sample underwent complete acid digestion; following the methodology outlined by Jarvis and Jarvis (1992) and Totland *et al.* (1992), the powdered sediment was treated overnight with HF followed by digestion with HNO_3 and dilution with deionised water. In order to check for reproducibility of results, a proportion of the samples were duplicated. Details of all the samples used in these analyses are listed in Appendix A.

5.3 Microfacies Classification Scheme

The analysis of thin sections has permitted a systematic categorisation of the sediments according to a modified classification scheme of mudrocks based upon the work of Hallam (1987) and Savrda and Bottjer (1991). The size distribution of the pyrite framboids and other forms of pyrite (see Wilkin *et al.*, 1996; Wignall and Newton, 1998) has also been characterised. Such an approach allows, on the basis of lamination type and thickness, extent of bioturbation, abundance of calcareous material in addition to pyrite characterisation, the effective reconstruction of palaeo-oxygenation histories together with an evaluation of palaeoecological and palaeoenvironmental change of these Lower Toarcian successions.

5.3.1 Lamination Types

Optical and backscattered electron imagery of the 40 Yorkshire samples reveals that the studied parts of the uppermost section of the Cleveland Ironstone Formation and the Whitby Mudstone Formation can be regarded as a mixture of two end members consisting of detrital terrigenous material (clay and silt) and organic matter. Pyrite also represents an important mineral phase in the Whitby Mudstone Formation. In a limited number of samples calcareous material was the dominant component.

Examination of the Dotternhausen and Truc de Balduc samples revealed a notable degree of similarity with the microfabrics identified from Yorkshire. In addition, these sections contained a fully oxygenated biofacies with a rich microfauna which is not seen in the Yorkshire samples.

Overall, the samples can be subdivided into eight microfacies types: Bituminous planar laminated mudstones (BPL); bituminous lensed mudstones (BLS); bituminous elongate streaked mudstones (BES); bituminous wavy laminated mudstones (BWY); restricted distinctly laminated mudstones (RDS); restricted indistinctly laminated mudstones (RIL); Beef (BF) and normal non-laminated mudstones (NNL).

Bituminous planar laminated mudstones (BPL)

This microfacies is characterised by abundant organic matter, including large wood fragments and distinct sharply based planar silt-rich fining-up cycles (typically 50-300 µm thick). These silt rich laminations containing abundant pyrite framboids and euhedral microcrysts, are sometimes cemented by patches of siderite (Pye and Krinsley, 1986) and contain abundant dolomite rhombs, which have subsequently been enclosed within a ferroan dolomite cement (Figure 28 m-n).

Bituminous lensed mudstones (BLS)

An abundance of organic matter, including large wood fragments which form discrete 'blebs' or lenses distinguishes this microfacies. Wood fragments commonly show evidence of compaction. Silt sized grains are sometimes frequent, but occur scattered throughout the sediment, rather than forming distinct horizons. Pyrite is common throughout, forming small (5-8 µm diameter) framboids (Figure 28 i-j).

Bituminous elongate streaked mudstones (BES)

The character of this microfacies is similar to the lensed lamination type (BLS) but in this category the organic laminae are much more elongate and form discrete continuous layers. Pyrite is again common throughout forming small framboids.

Bituminous wavy laminated mudstones (BWY)

This microfacies is typified by abundant organic matter, including large wood fragments and has a distinctive wavy appearance to the laminations. This may be a result of abundance of observed microbial mats (O'Brien, 1990) although Wignall (1994) and

Schieber (1999) suggest that this characteristic relief is more likely to have been induced by the differential compaction of organic matter around the silt/carbonate aggregates.

Restricted distinctly laminated mudstones (RDS)

Although this microfacies contains a large percentage of pyrite and laminations are relatively distinct, the organic material present is greatly reduced compared to the microfacies outlined above. Silt sized grains occur within diffuse horizons and locally calcareous blebs are present. Pyrite occurs mainly as burrow infills and replacement textures rather than being framboidal.

Restricted indistinctly laminated mudstone (RIL)

While still containing pyrite occurring chiefly as burrow infills and replacement textures rather than framboidal, these silt-rich mudstones, frequently are bioturbated and hence display indistinct laminations or are completely unlaminated.

'Beef'

This microfacies is typified by abundant fibrous calcite material forming a dense fabric. Occasional small bivalve shell material can be observed, which has been partially replaced by pyrite, which itself has been enveloped by the replacive fibrous calcite fabric. Because of the high percentage of calcareous material present the high organic matter and clay mineral content are greatly reduced.

These features are indicative of poorly-developed 'Beef' (J. Macquaker, *pers. comm.*) where fibrous calcite nucleates on bivalve fragments. Similar fabrics are also seen to occur in other organic-rich systems: the classic Shales-with-'Beef' of the Dorset Coast also occurs within organic rich shales (Callomon and Cope, 1995; Hesselbo and Jenkyns, 1995) and is considered by these authors to be of early diagenetic origin.

Vertically orientated fibrous calcite in the form of concretions can result in the development of cone-in-cone structures. Well developed cone-in-cone structures are also observed on the Yorkshire Coast, south of Ravenscar, at the base of the *bifrons* Zone. The mechanisms for the origin of fibrous calcite veins and cone-in-cone structures and indeed the origins of concretionary bodies in general are still debated and puzzling. In the case of large concretionary bodies, like the Whalestones of the Jet Rock *s.s,* it is difficult to appreciate how these could grow while the host sediment thins down by compaction.

Sellés-Martínez (1996) attempts to answer these problems by proposing the Syncompactional Concretionary Growth model. In this model large porosities are preserved over very long time spans and down to depths that are somewhat greater than expected, due to the inhibition of normal compaction caused by early overpressuring. The overpressuring is the result of the development of hydraulic seals.

Cone-in-cone structures would then result from mechanical fracture of the material forming layer parallel veins and rims of concretions. Conical fractures in this model result from the effect of overburden load (formerly supported by fluid pressure during vein or rim growth) on the detrital skeleton. Shear stresses fracture the rigid crystalline material but not the host layer (still wet and uncemented). It is therefore conceivable that differences between 'cells' could result in the variation in the formation of concretions.

Within this microfacies pyrite forming small (2-10μm diameter) framboids is common. It is of note that this identical calcite fabric was observed within organic rich sediments of the *falciferum* Zone of the Lower Toarcian in both Yorkshire and Truc de Balduc.

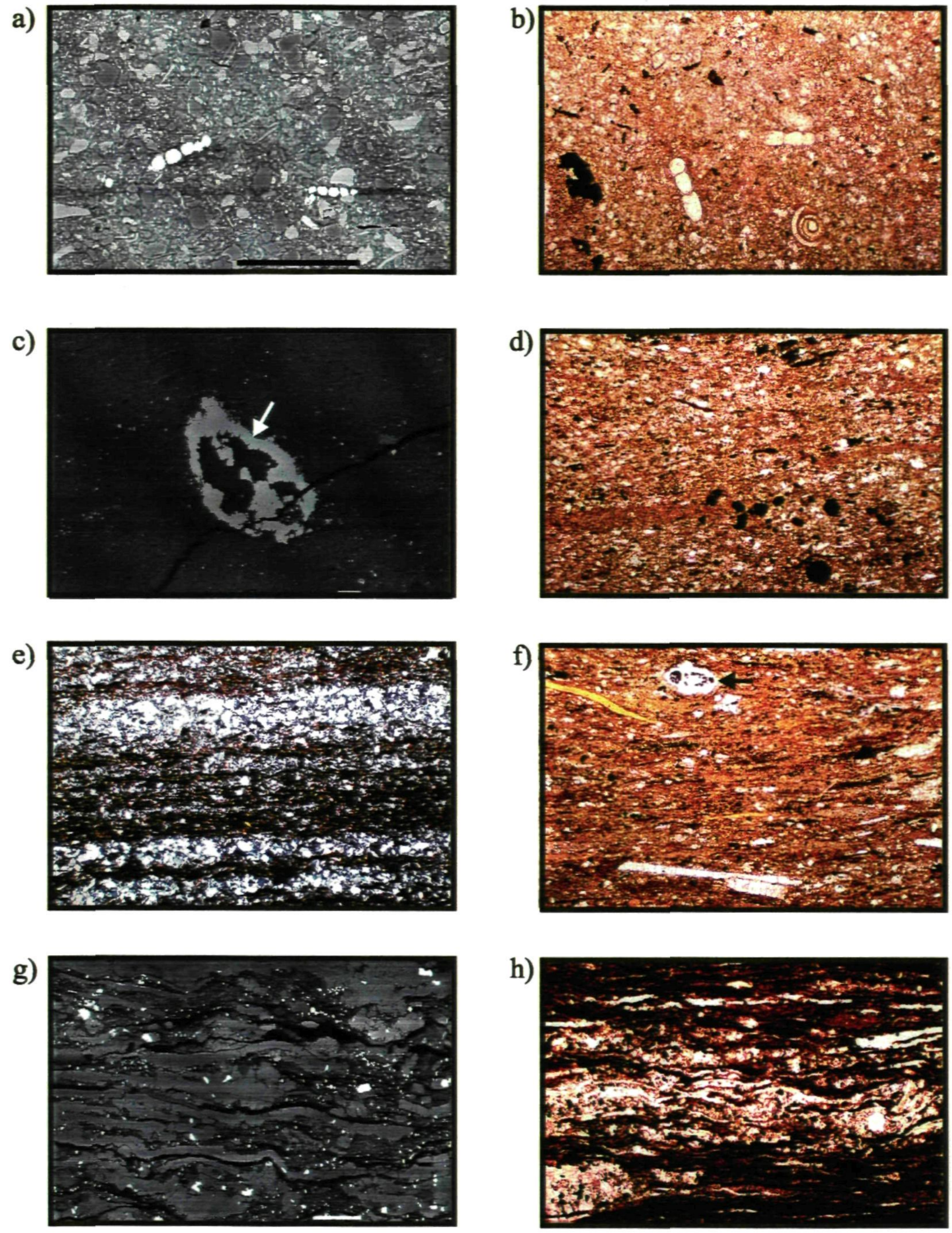


Figure 28. BSEM images and optical photomicrographs of microfacies. All photomicrographs in PPL unless otherwise stated. **a)** BSEM image of normal non-laminated microfacies (NNL), Truc de Balduc, *hawskerense* Subzone. Scale bar 100µm. **b)** Optical photomicrograph of NNL, Dotternhausen, *paltum* Subzone. Field of view 0.97mm. **c)** BSEM, restricted indistinctly laminated microfacies (RIL), Cement Shales, south of Peak, *fibulatum* Subzone. Scale bar 100µm. Pyritised burrow arrowed. **d)** Optical photomicrograph of RIL, Cement Shales, south of Peak, *fibulatum* Subzone. Field of view 0.97mm. **e-f)** Optical photomicrographs of restricted distinctly laminted microfacies (RDL). e. Crossed polars view. Grey Shale Member, Brackenberry Wyke, *paltum* Subzone. Field of view 2.5mm. f. Dotternhausen, *falciferum* Subzone. Field of view 0.97mm. Foraminiferal test arrowed. **g)** BSEM image of Bituminous wavy microfacies (BWY), Bituminous Shales, Port Mulgrave, *falciferum* Subzone. Scale bar 100µm. **h)** Optical photomicrograph of previous sample. Field of view 1.29mm.

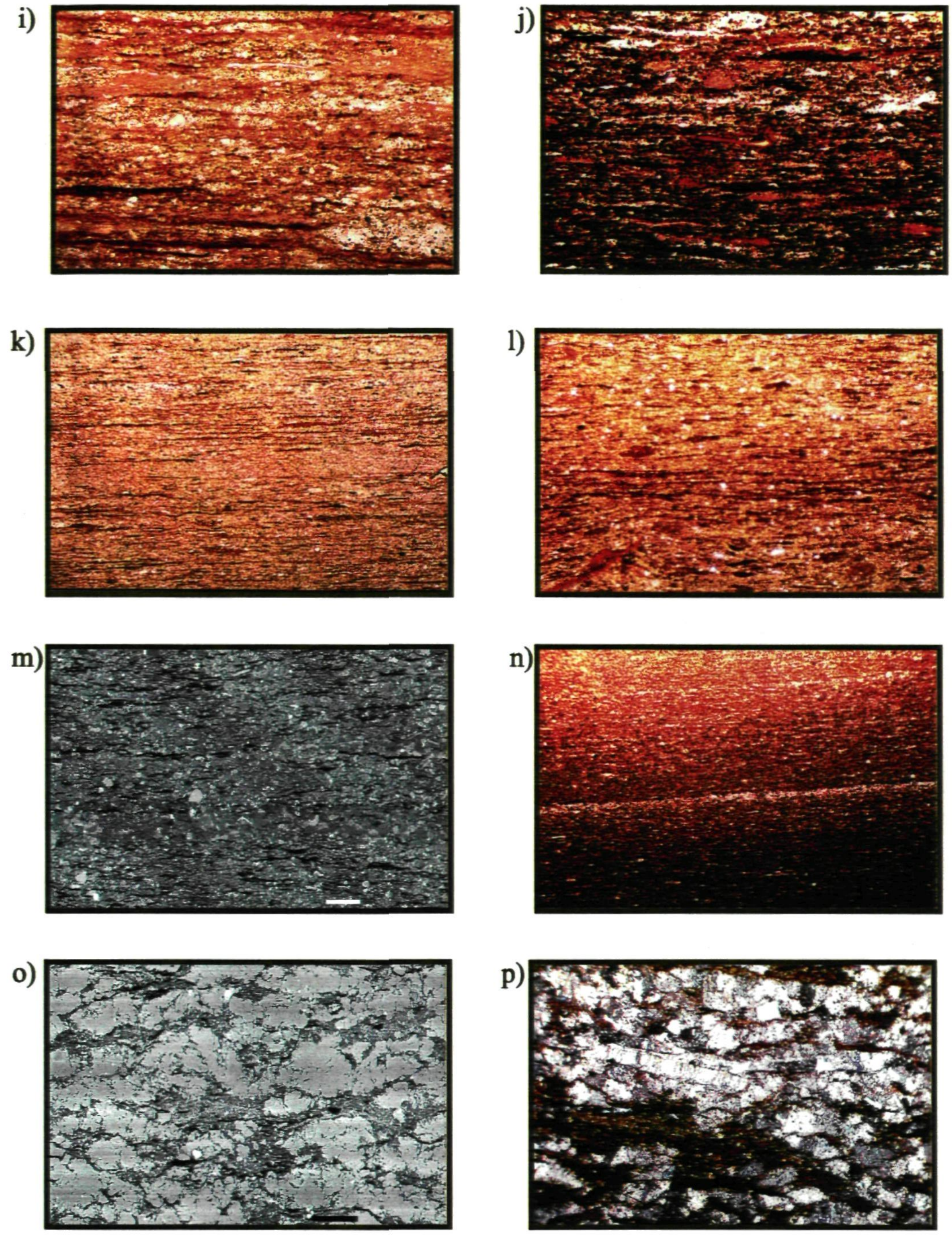


Figure 28 continued. **i-j**) Optical photomicrographs of Bituminous lensed microfacies (BLS). i. Truc de Balduc, *exaratum* Subzone. Field of view 2.5mm. j. Jet Rock s.s, Port Mulgrave, *exaratum* Subzone. Field of view 1.29mm. **k-l**) Optical photomicrographs of Bituminous elongate streaky microfacies (BES). k. Bituminous Shales, Port Mulgrave, *falciferum* Zone, Field of view 2.5mm. l. Peak Stones, south of Peak, *falciferum* Subzone. Field of view 2.5mm. **m**) BSEM image of Bituminous planar microfacies (BPL), Jet Rock *s.s.*, Port Mulgrave, Lower Pseudovertebrae, *exaratum* Subzone. Scale bar 100μm. **n**) Optical photomicrograph of BPL. Jet Rock *s.s.*, Port Mulgrave, *exaratum* Subzone. field of view 3.3mm. **o**) BSEM image of 'Beef', fibrous calcite (BF) microfacies. Millstones, Port Mulgrave, *exaratum* Subzone. Scale bar 100μm. **p**) Optical photomicrograph in crossed polars of previous sample. Field of view 1.29mm.

Normal Non-laminated (NNL)

This category includes all bioturbated mudstones with an homogenous texture containing foraminiferal tests, other shell fragments, crinoid ossicles and echinoderm spines.

The features of each type are shown in Figure 28a-p and all views shown are of sections cut perpendicular to bedding. Vertical variation of the types determined for the Yorkshire Coast, Dotternhausen and Truc de Balduc are shown in Figure 29a-c. The classification scheme proposed for this study in Table 6 defines the shale facies types, microfacies types and consequently their faunal component and corresponding oxygenation level. The five oxygen-related biofacies are used in the sense of Savrda and Bottjer (1991) and are modified for this study as follows:

- Anaerobic biofacies: well laminated strata lacking in situ macro- and microbenthic body fossils and microbioturbation.
- Quasi-anaerobic biofacies: laminated strata, subtly disrupted by microbioturbation, containing microbenthic body fossils.
- Exaerobic biofacies: laminated strata similar to that of anaerobic or quasi-aerobic biofacies. Macro-fossil shell fragments present.
- Dysaerobic biofacies: bioturbated strata characterised by low-diversity assemblages of microbenthic body fossils.
- Aerobic biofacies: bioturbated strata containing diverse microbenthic body fossils and evidence for macrobenthic organisms (e.g., brachiopod shell fragments).

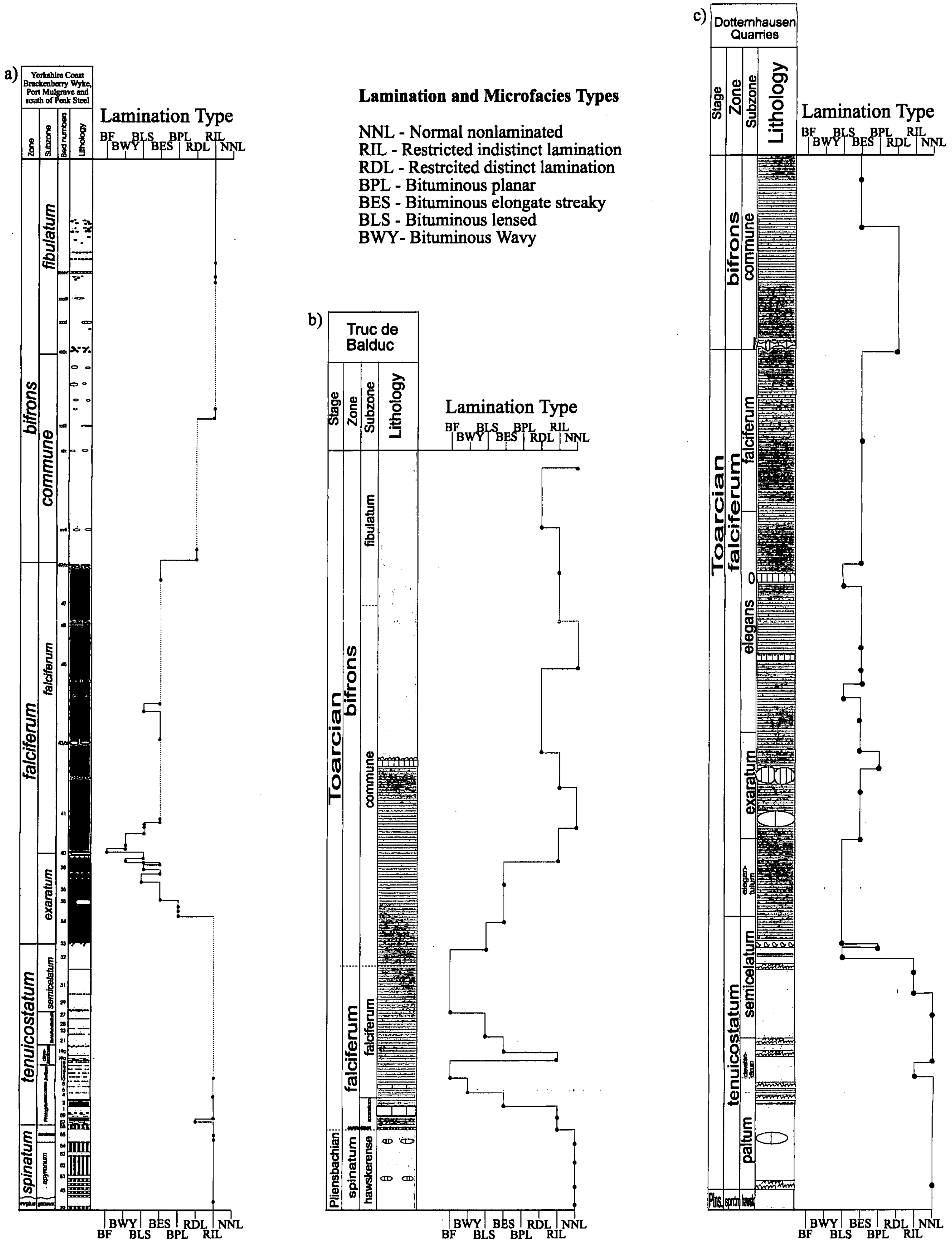


Figure 29. Vertical variation of lamination types for a) Yorkshire Coast. Composite log of Brackenberry Wyke, Port Mulgrave and south of Peak Steel (Ravenscar); b) Truc de Balduc, southern France; c) Dotternhausen Quarries. See Figs 14-17 for key. For explanation of lamination types, see Table 6 and section 5.3.1.

In practice, however, is was not possible to distinguish between exaerobic and quasi-anaerobic biofacies. These biofacies types were then compared with the Oxygen Restricted Biofacies (ORB) of Wignall and Hallam (1991).

Shale Facies	Micro-laminations	Microbioturbation	Oxygen related biofacies[1]	ORB (after Wignall & Hallam, 1991)	Microfacies (This study)
Normal	Non-laminated	Highly bioturbated	Aerobic	-	NNL
Restricted (pyritous)	Indistinct	Burrowed	Dysaerobic	5-6	RIL
	Distinct	Disruption of laminations	Quasi-anaerobic	3-4	RDL
Bituminous (organic rich)	Wavy	Algal Mats	Anaerobic	1-2	BWY
	Lenses	None	Anaerobic	1-2	BLS
	Elongate Streaks	None	Anaerobic	1-2	BES
	Planar	None	Anaerobic	1-2	BPL
	Beef	None	Anaerobic	1-2	BF

Table. 6. Microfacies classification scheme. [1]Oxygen related biofacies after Savrda and Bottjer (1991).

The six ORB's of the Wignall and Hallam (1991) scheme are primarily defined by their species diversity. Two anaerobic biofacies, defined by a complete absence of any benthic organisms are recognised in the biofacies scheme. ORB1 contains only taxa considered to have led a truly pelagic existence (for example fish, conodonts, graptolites). The absence of potential nektobenthic forms suggests that ORB1 may record euxinic conditions. ORB2 differs in containing taxa regarded as nektobenthic life strategists (for example, ammonites, belemnites and demersal fish), thus precluding the presence of a substantial volume of sulphidic lower water column. Lower dysaerobic ORBs contain impoverished and, in the case of ORB3, rare benthic assemblages commonly dominated by bivalves in the Mesozoic. An important attribute of ORBs 3 and 4 is the restriction of benthic fossils to a few bedding planes in strata that are commonly laminated and lack bioturbation. Upper dysaerobic biofacies record a slight increase in benthic species richness and a marked change in the sediments fabric. Thus, ORB5 is developed in homogenous mudstones in which pervasive bioturbation has destroyed evidence of lamination and benthic fossils are recorded at every level in the strata. This implies that bottom waters were persistently dysoxic (rather than intermittently so, as in ORBs 3 and 4) allowing prolonged colonisation by benthic macrofauna and a mobile infauna. Normally oxygenated facies are distinguished from ORB 6 by their higher benthic diversity.

5.3.2 Microfacies Interpretation and Distribution

Examination of the microfacies from Truc de Balduc, Dotternhausen and the Yorkshire coast permits the following observations. The vertical progression from thick lamination to wavy lamination and to fine lamination is interpreted as being the result of a change in sedimentary processes from the initial dominance of bottom current action, to an increase in organic matter and finally to suspension settling in deeper offshore water.

Within the well laminated organic rich microfacies, framboidal pyrite is observed to be the dominant type present and ranges in size from 1 - 16μm (see section 5.4). This narrow size range may reflect relatively short growth times, suggesting that most pyrite in these facies formed near the sediment/water interface under conditions of supersaturation with respect to pyrite (Wilkin and Barnes 1997; Wignall and Newton 1998). Within the less restricted microfacies (dominant in the Mulgrave and Alum Shales Members), pyrite framboids are also pervasive. However, other fabrics are present, including large pyritic masses replacing shell fragments, infilling of pore spaces and burrow infill, possibly reflecting an origin in a dysaerobic/anaerobic environment where biogenic degradation aided the development of suitable conditions for pyrite growth.

The microfacies observed at Truc de Balduc and Dotternhausen show a lesser degree of variation than the Yorkshire section. No examples of the bituminous planar microfacies were seen and there was no evidence of the degree of development of the bituminous wavy microfacies seen in the Jet Rock *s.s.* During the deposition of the Jet Rock *s.s.* shales, conditions were such that continuous sedimentation of organic-rich clays was periodically interrupted by deposition of silt (O'Brien and Slatt, 1990). The planar lamination in Figure 28m-n provides evidence of systematic alternation of sedimentary conditions, possibly indicating periodic pulses of coarser sediment deposited rapidly into the aerobic environment. The shallow, basinal settings of Truc de Balduc and Dotternhausen may have influenced the development of the lamination types, coupled with the distance from surrounding highs and a consequent lack of clastic input.

Evidence for depositional cycles, originating from marine turbidites, can be seen in the microfacies from the Grey Shale Member (Figure 28e). The graded bedding and undulating contacts between light coloured silt-rich layers and the darker coloured organic-rich layers reflect episodic sedimentation. The fine-grained nature of the shale suggests either deposition from low density turbidity currents onto the slope, or from distal turbidites flowing out into the basin.

5.4 Pyrite Analysis

As noted in the previous section, it is difficult to distinguish between euxinic (height of water column anoxia) conditions in mudrocks, where the lower water column is hydrogen sulfide bearing and oxygen free, from oxygen-poor (dysoxic) conditions or anoxic, non-sulfidic conditions. A relatively simple method of determining the level of oxygen deficiency was proposed by Wignall and Newton (1998) using pyrite framboid diameter. Framboids are densely-packed, raspberry-like, spherical aggregates of equigranular, micron-size crystals or microcrysts. They range from a few microns to several tens of microns in diameter. The closely packed, spherical aggregates of uniform-sized microcrysts were defined by Wignall and Newton as 'Type 1' framboids to distinguish them from rarer, generally larger variants of framboids displaying much less dense packing. These 'Type 2' framboids showed evidence of compaction and a much wider range of microcryst sizes in contrast to the equigranular microcrysts of type 1 framboids.

Wignall and Newton (1998) examined the size distribution of framboids and other forms of pyrite in the Kimmeridge Clay Formation (Upper Jurassic, Kimmeridge Bay, southern England) and correlated them with the oxygen-restricted biofacies (ORB) scheme of Wignall and Hallam, (1991), described in Table 4. The ORBs were used to provide an independent assessment of bottom water oxygen levels with which to compare the framboid size distributions. Variations in size-frequency distributions of the Kimmeridge Clay framboids revealed a close correspondence between type 1 framboid diameters only and ORBs:

- ORBs 1 to 4 show a narrow size range with mean values around 3μm and few framboids greater than 5μm.
- The transition to upper dysaerobic ORBs is marked by a dramatic increase of framboid size and the loss of framboids of less than 3μm.

Maximum framboid diameter (MFD) is also thought to be a good indicator of biofacies that can also distinguish anaerobic and lower dysaerobic ORBs. ORBs 1 to 4 have a similar framboid size-frequency distribution, but MFD is considerably greater in the lower dysaerobic ORBs due to the presence of rare, large framboids presumed to have formed in the sediment. MFD increases markedly in ORB 5 with a substantial proportion of framboids exceeding 10μm diameter.

Wignall and Newton (1998) also investigated the usefulness of type 2 framboids and non-framboidal, diagenetic pyrite (microcrysts and "amorphous lumps") but found no apparent correspondence between size fluctuations and changes in the ORBs or the lithologies.

Although note was taken of these pyrite forms during this study, the results were not considered in any quantitative sense (see Section 5.3.1).

5.4.1 Analytical procedure

Framboid diameter was measured on polished thin-sections using a JEOL 6100 scanning electron microscope (SEM) set to display a backscattered electron (BSE) image. Type 1 framboids were then measured from a digital image captured with a JEOL SemAfore digital image recording system using a mouse-operated, screen based, measuring tool. Each sample was analysed until around 100 Type 1 framboids had been measured. Seven thin-sections were analysed from the Yorkshire coast section covering the Grey Shale, Mulgrave Shale and Alum Shale Members of the Whitby Mudstone Formation (see Figs 11 and 30).

5.4.2 Results

The size-frequency distribution of Whitby Mudstone framboids is shown in Figure 30 and appears to provide good evidence for the development of euxinicity in the organic-rich facies of the Jet Rock *s.s.*, *exaratum* Subzone. Sample BRW 1/11 exhibits well developed upper dysaerobic framboid types. The MFD is very large compared to the other samples and there is a lack of any of the small diameter framboids that characterise the distributions of the samples in the Jet Rock *s.s.* (PMG 1/10, PMG 1/2 and PMG 1/13). These latter samples have a framboid size-frequency distribution that clusters around the smaller sizes with none of the large diameter framboids. This indicates that the framboids must have grown within euxinic conditions with a lack of oxygen in the lower water column. The *falciferum* Subzone displays a gradual increase in the level of oxygen in the water column

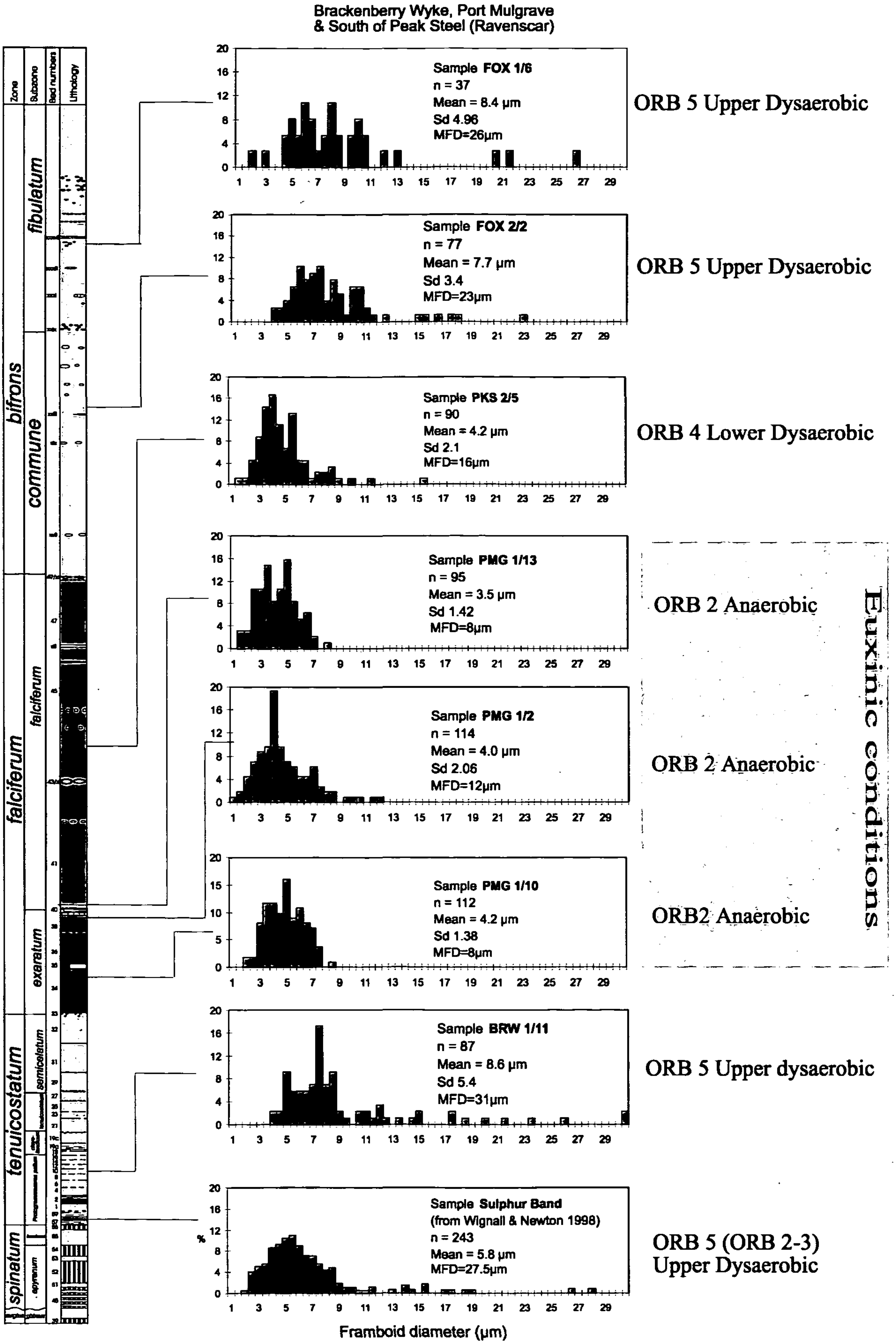


Figure 30. Size-frequency distribution of type 1 framboids and corresponding ORBs from the North Yorkshire Coast section. n = sample size; Sd = Standard deviation; MFD = maximum framboids diameter. For lithostratigraphy and key see Fig. 14.

with sample PKS 2/5 displaying an intermediate distribution of framboid sizes between the euxinic conditions of the Jet Rock *s.s.* and the lower dysaerobic conditions of the *bifrons* Zone. The trend towards more oxygenated conditions continues to develop throughout the *bifrons* Zone as indicated by the framboid size-frequency distributions of samples FOX 2/2 and FOX 1/6. Here, the MFD reaches 23 - 26μm respectively while the small size fractions are lost.

The transition from upper dysaerobic to anaerobic ORBs is marked by a dramatic decrease of average framboid size and the loss of the framboids greater than 12μm. Generally, the data show a good correlation between ORBs and framboid size diameters. The variations in size-frequency distributions of the North Yorkshire Coast successions, therefore, reveal a close correspondence between type 1 framboids diameters and ORBs.

5.5 Geochemical Characterisation

The geochemical data from the Yorkshire Coast sections are presented in Figure 31. Reproducibility, based upon replicate analysis, was estimated generally to be less than ± 12% of the measured concentration of Ca and Fe and ± 5% for Mg, Mn, Ba and Al.

Al concentration is thought to be a reasonably good measure of the detrital flux: i.e., as a proxy for the presence of aluminosilicates (Brumsack, 1991; Bellanca, *et al.*, 1999). Ba, Mn, Sr, Mg and Fe are consequently expressed as element/Al ratios to identify their distribution with respect to factors other than those associated with the original detrital flux. The data are in general agreement with other studies investigating the geochemistry of the Whitby Mudstone Formation of the Yorkshire coast (e.g., Gad *et al.*, 1969; Pye and Krinsley, 1986). Al values show an overall increase from the uppermost Cleveland Ironstone Formation to the upper part of the studied section of the Alum Shale Member (Figure 31). Two decreases of Al concentrations are observed, centered upon the iron-rich parts of the Cleveland Ironstone Formation and within the Millstones located at the top of the *exaratum* Subzone (the uppermost part of the Jet Rock *s.s.*). Al values showing minimum concentrations at this horizon are possibly indicative of a reduced amount of clastic input. Ca shows an increase through the Cleveland Ironstone Formation and is in contrast to the Al maximum values centered on the Millstones. Subsequent Ca values fluctuate, but generally show a decrease through the overlying Mulgrave and Alum Shales Members. Mn/Al, Fe/Al and Mg/Al ratios all show a close correlation and display expected high values within the Cleveland Ironstone Formation. Higher than background values are also observed within the Jet Rock, compared with the overlying Mulgrave and Alum Shales Members. One large peak is centered on the Millstones. Sr/Al ratios also show a large increase at this point. Ba/Al ratios generally show low values, but three distinct peaks are observed (Figure 31), two within the Jet Rock, which are notably not synchronous with the observed increases in Ca and other elements, but straddle this peak. A single high Ba/Al ratio is observed in the Alum Shale Member. However, Bellanca *et al.* (1999) find that Ba (along with Sr and Mn) lack any correlation with Al, suggesting that their distribution is dominated by factors different from the original detrital flux. Rather, these elements are involved in processes of reminerallisation of biogenic and authigenic phases. Ba enrichments in sedimentary deposits can be considered as indicators of high flux of biogenic material to the sediments and therefore of high surface-water productivity (Schmitz, 1987; Dymond *et al.,* 1992; Van Os *et al.,* 1994). The Ba peaks observed from the North Yorkshire coast also appear independent of other elements and could therefore be interpreted in terms of increased surface-water productivity.

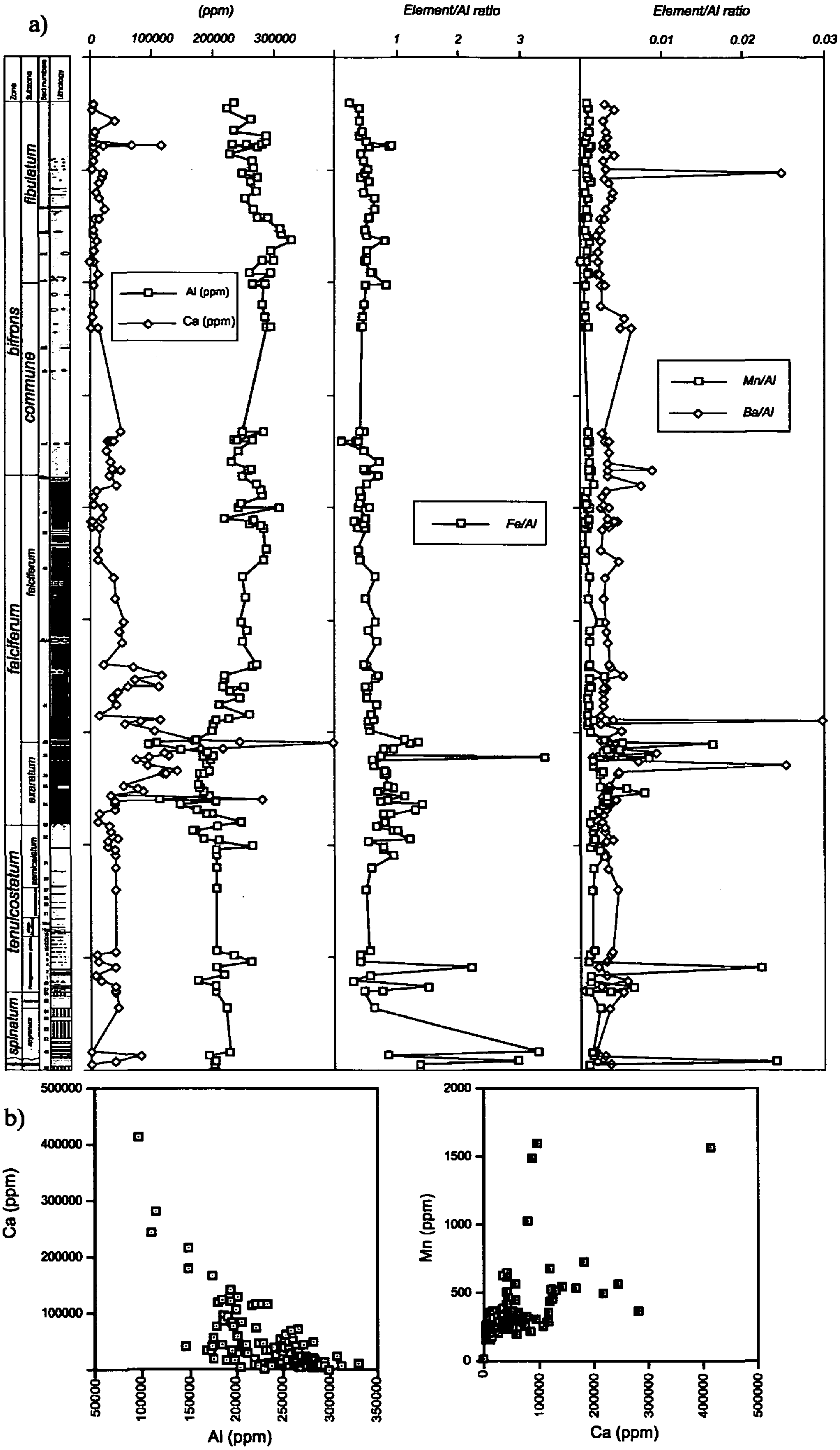


Figure 31. a) Geochemical data from the Pliensbachian - Toarcian of the North Yorkshire Coast. Trace elements are expressed as element/Al ratios for Fe, Mn and Ba. b) Cross plots of Al/Ca and Mn/Ca.

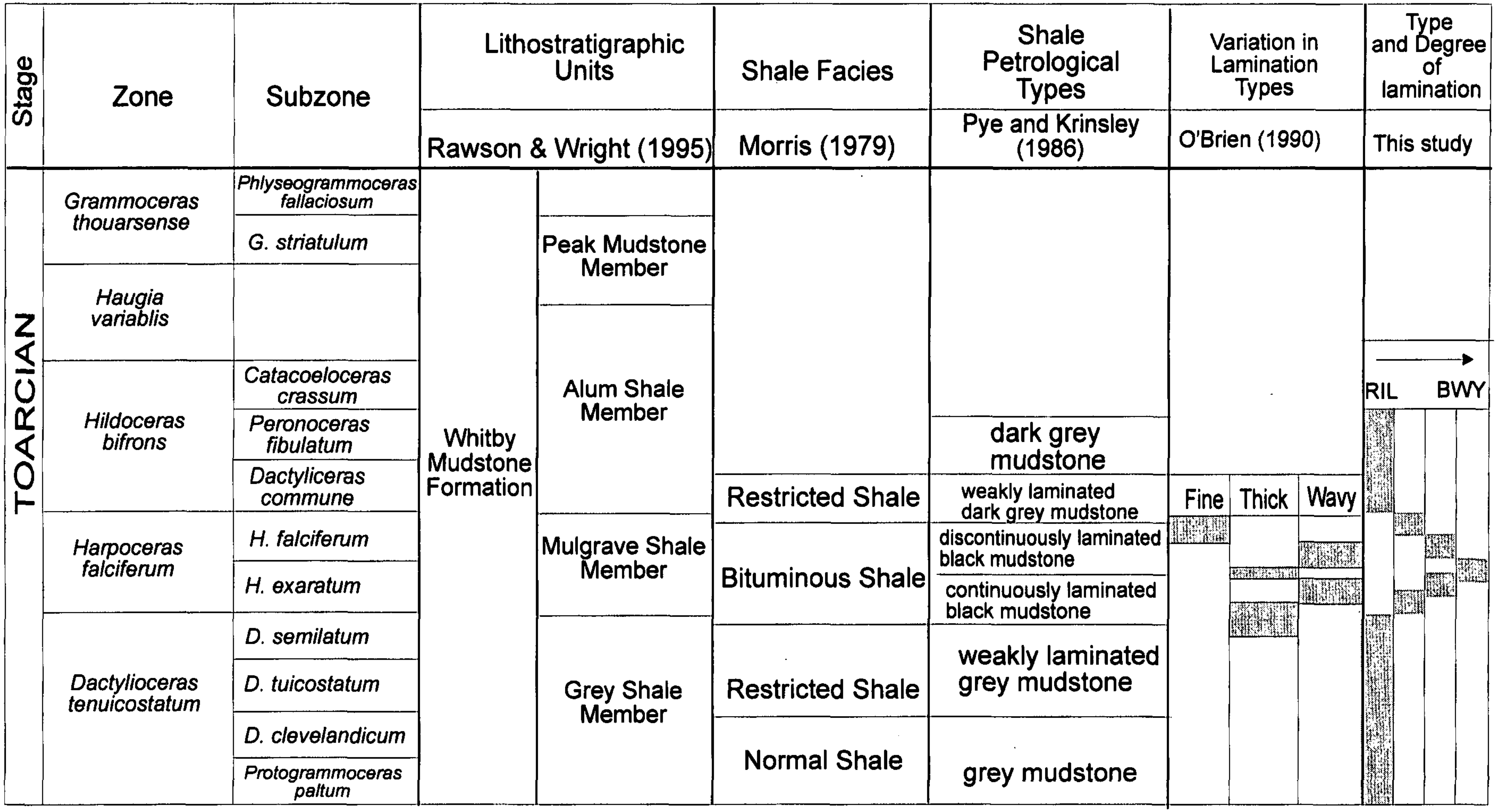
The co-occurrence of the higher Ba/Al concentrations within the Jet Rock *s.s.* and peaks of Mn/Al, Fe/Al and Mg/Al probably identify a stage, within the Toarcian anoxic event, of maximum oxygen depletion at the sea-floor associated with high fertility in surface waters.

5.6 Palaeoenvironmental interpretation

5.6.1 Microfacies

Lamination in shales is an important feature in providing clues to ancient sedimentary environments and processes where changes in sedimentary processes give rise to variations in the types of laminations (O'Brien, 1990). Hallam (1987) presented a classification of mudrocks based in part upon degree of lamination or bioturbation and also upon the character of benthic microfauna. He describes laminites (barren and shelly) which display well developed alternation of kerogen and clay/calcite laminae, shelly shale, which possesses moderate to poorly developed and often discontinuous organic laminae and shelly mudstone with no organic laminae. Hallam's (1987) interpretation is that many laminites formed in anoxic water and that the microlamination is annual in origin, related in most cases to seasonal blooms of plankton. Thin laminae (usually less than 3-4 mm), called rhythmites by Reineck and Singh (1972), represent regular changes in the transport or production of material and record differences in composition, texture and colour.

O'Brien (1980) presented a detailed fabric (i.e., particle orientation) description of lamination of Toarcian shales of the Yorkshire coast sections, at Port Mulgrave and Ravenscar. An earlier classification of these shales was proposed by Morris (1979) based primarily upon body fossils, trace fossils and other sedimentological features exclusive of lamination. O'Brien's (1990) classification identified three lamination types: fine (>1mm), thick (>1mm) and wavy (<1mm). The vertical occurrences of these lamination types are



Stage	Zone	Subzone	Lithostratigraphic Units		Shale Facies	Shale Petrological Types	Variation in Lamination Types			Type and Degree of lamination
			Rawson & Wright (1995)		Morris (1979)	Pye and Krinsley (1986)	O'Brien (1990)			This study
TOARCIAN	*Grammoceras thouarsense*	*Phlyseogrammoceras fallaciosum*	Whitby Mudstone Formation							
		G. striatulum		Peak Mudstone Member						
	Haugia variablis			Alum Shale Member						RIL → BWY
	Hildoceras bifrons	*Catacoeloceras crassum*								
		Peronoceras fibulatum				dark grey mudstone				
		Dactyliceras commune			Restricted Shale	weakly laminated dark grey mudstone	Fine	Thick	Wavy	
	Harpoceras falciferum	*H. falciferum*		Mulgrave Shale Member	Bituminous Shale	discontinuously laminated black mudstone				
		H. exaratum				continuously laminated black mudstone				
	Dactylioceras tenuicostatum	*D. semilatum*		Grey Shale Member	Restricted Shale	weakly laminated grey mudstone				
		D. tuicostatum								
		D. clevelandicum			Normal Shale	grey mudstone				
		Protogrammoceras paltum								

Figure 32. Comparison of facies classification schemes. Lithostratigraphic units in the Whitby Mudstone Formation as defined by Rawson and Wright (1995) and their relationships to the facies classification schemes of Morris (1979), Pye and Krinsley (1986), O'Brien (1990) and the results of this study (See Figures 28-29 for explanation of lamination types).

illustrated in Figure 32 in comparison with other published classification schemes and the results of this study.

The vertical progression from thick lamination to wavy lamination and to fine lamination is interpreted to be a result of a change in sedimentary processes from the initial dominance of bottom current action, to activity by benthic microbial mats and finally to suspension settling in deeper offshore water.

The shales of the Posidonienschiefer were divided by Röhl (1998) into mudstones, bituminous mudstones and oil shales (Ölschiefer). Laminations were characterised as fine (< 0.1 mm), rough (> 0.1 mm), wavy (< 0.1 mm), lens-shaped or indistinct. These definitions differ from those of O'Brien (1990) as do the environmental interpretations. O'Brien's fine laminations of >1mm do not occur in the Posidonienschiefer of Dotternhausen except in the wavy or lens-shaped laminations. In the case of clearly defined laminations O'Brien (1990) supposes a deep quiet water environment of deposition. For the rough laminations O'Brien proposes a flow influenced offshore area while a low energy, calm environment is given for the wavy laminations. Indistinct laminations are limited to the bituminous mudstones and indicate moderate water energy levels due to intensified circulation in the water body while the distinct wavy and lens-shaped laminations indicate deeper water, quiet conditions within a reducing environment.

Both schemes indicate that the differences in the lamination types can be interpreted in terms of depositional environments, related to the facies development during the Toarcian transgressions. The disagreements can be attributed to the different water depths and energy levels between the two depositional basins. Röhl (1998) assumes a shallower, more proximal setting for the Ölschiefer than O'Brien (1990) does for the Jet Rock. Röhl's (1998) assumptions would seem to be confirmed by the results of this study.

The overall facies changes through the Alum Shale Member are an indication of increasing bottom-water oxygenation (Pye and Krinsley 1986), while during this interval in the Posidonienschiefer and Schiste Cartons, the oxygenation level fluctuated considerably.

5.6.2 Pyrite Analysis

With the exception of the oxic zone, all sediments pass through the same stages of diagenesis beneath oxygenated and anoxic waters. However, the resultant sedimentary chemistry is highly distinctive (Wignall, 1994). Beneath fully oxygenated bottom waters most sedimentary iron sulphides are re-oxidised at the redox boundary and never incorporated into the geological record. Similarly, in dysoxic conditions, pyrite is constantly oxidised and re-precipitated; only in voids such as the internal chambers of ammonites does pyrite avoid oxidation. In anoxic conditions virtually all pyrite is preserved, including the prolific numbers of microscopic framboids observed. This relationship can be exploited to provide clues to the environmental conditions (Table 7). While there has been little attempt to distinguish between conditions of stable low-oxygen environments (dysaerobic facies) and fluctuating low-oxygen/anoxic environments (poikiloaerobic facies), the presence or absence of burrowers is thought to be one of the fundamental controls on facies type (Wignall, 1994). Anoxic conditions are *apparent* on the basis of the presence of lamination and the absence of *in-situ* macrobenthic body fossils. However, upon closer examination, the microfauna and/or microbioturbation may demonstrate that conditions were not absolutely anoxic (Savrda and Bottjer, 1991). Examination of the lamination types (Section 5.3.1) provides evidence for the continued existence of the most anoxic (anaerobic) conditions. This is the biofacies that develops in the absence of oxygen (zero bottom-water dissolved oxygen).

Environment	Euxinic	Anoxic	Dysoxic				Oxic
Biofacies ORBs	1	2	3	4	5	6	
Pyrite	abundant framboids and minute crystals of pyrite				pyrite only fills voids		little or no pyrite

Table 7. Relationship between palaeoeologically defined oxygen-restricted biofacies (ORBs) and pyrite phenomena, after Wignall (1994). See Table 6 for description of ORBs.

The abundance of pyrite in the Toarcian sediments (especially the Jet Rock *s.s.*) of the Yorkshire Coast suggests that anoxic conditions extended up to the sediment surface (c.f., Morris, 1980) which could explain the lack of infauna in the sediment.

These results also indicate that the onset of anoxia and the development of euxinic conditions occurred rapidly while the recovery back to oxygenated conditions was much less rapid. Lower and upper dysaerobic conditions continued to dominate the Alum Shales of the *bifrons* Zone.

5.6.3 Trace element variation

The trace metal geochemistry of organic rich shales may provide information regarding their environment of deposition. Certain assumptions concerning the origin of metal enrichments in such sediments require an understanding of geochemical cycles, as well as information regarding early diagenetic processes (Brumsack 1991).

Mn, in carbonate dominated sequences, has been considered to be a robust indicator of sea level change (Jarvis and Murphy, 1999), related to increases in Mn being associated with condensed sequences and sea level high stands or maximum flooding surfaces (Pratt *et al.*, 1988; but see also Calvert and Pedersen, 1993). The occurrence and significance of Mn within mudstone dominated sequences is less clear. Mn-rich carbonates are thought to form in poorly oxygenated sediments owing to a rise in pore-water alkalinity after organic matter mineralisation (Froelich *et al.*, 1979). A concentration of Mn and Mn-rich carbonates are observed in Lower Toarcian carbon-rich deposits from Europe (e.g., Jenkyns, 1988; Bellanca *et al.*, 1999) possibly due to delivery of reducible Mn to the deeper anoxic horizons, from the oxic waters above the redox boundary (Force and Cannon, 1988; Jenkyns *et al.*, 1991; Calvert and Pedersen, 1993). However, in spite of the accumulation of dissolved Mn in the bottom waters of anoxic basins, the concentrations of Mn do not reach levels that would permit the precipitation of an Mn2+ solid phase (i.e., MnCO3) in the waters or the sediments (Calvert and Pedersen, 1993). Hence, the concentration of Mn in pelagic sediments may be due to the slow accumulation rates of terrestrial and biogenic detritus relative to the precipitation from seawater of authigenic Mn under oxic conditions (Calvert and Pedersen, 1996).

The observed positive correlation of Mn with Ca (Figure 31b) suggests that Mn within the sediments is mainly fixed in the carbonate lattice of the calcareous material. Hence observed Mn spikes, may not be indicative of peak anoxic conditions but possibly as a response of increases in the carbonate content.

The enrichment of Ca in this system is likely to arise from a number of sources including biogenic input. Observed macrofossil Ca sources comprise pyritised ammonites, associated with belemnites and bivalves and foraminifera. The physical expression of this input can be seen in the fibrous calcite 'Beef' texture and siderite seen occasionally as patches of cement in the more silty sediments and as randomly dispersed rhombs (Pye and Krinsley 1986).

The Hard Shales and the Cement Shales of the Alum Shale Member (Figure 28a), according to Hesselbo & Jenkyns, (1995), have a higher carbonate content and abundant calcite concretionary horizons. An increase in Ca was not evident in this study, in this part of the succession, but as noted above, concretions were avoided in the sampling programme.

Maxima of Ca and Mn occur at the base of the *falciferum* Subzone. Al values show minimum values at this horizon, indicative of a reduced amount of clay input. As noted above, the lithofacies at this horizon consists of a cemented laminated shale. It is suggested that these maxima are an artifact of condensation of carbonate fossiliferous material due to sediment starvation and correspond to published estimates of the maximum flooding surface of Wignall and Maynard (1993). These authors note that this horizon was unusually rich in belemnites and use this as criteria for inferring the presence of a maximum flooding surface at this point. Hesselbo and Jenkyns (1998) however, found no evidence that the top of the *exaratum* Subzone in the Cleveland Basin is abnormally belemnitiferous. Neither did they find any support for condensation at this level from a consideration of the subzonal thicknesses and instead preferred an interpretation consequential upon rapid relative sea-level rise and sediment starvation. While sequence stratigraphic interpretations of organic-rich shales can be somewhat obscure (Wignall, 994; Hesselbo and Jenkyns, 1998) Figure 33 illustrates the differing interpretations discussed and those reached during this study.

Increased barium levels in the world oceans have been associated with increased productivity (e.g., Chan *et al.*, 1977) due to direct secretion of barite by planktonic biota and precipitation within the microenvironment of decaying organic debris and documented using Ba/Ca ratios in coralline aragonite (e.g., Lea *et al.*, 1989). If phytoplankton blooms are accompanied by substantial fluxes of Ba, more of this element should be available for inclusion in the sediments but not necessarily associated with an increase in Ca. This factor may account for the observation that high levels of Ca do not necessarily correlate with the peaks of Ba.

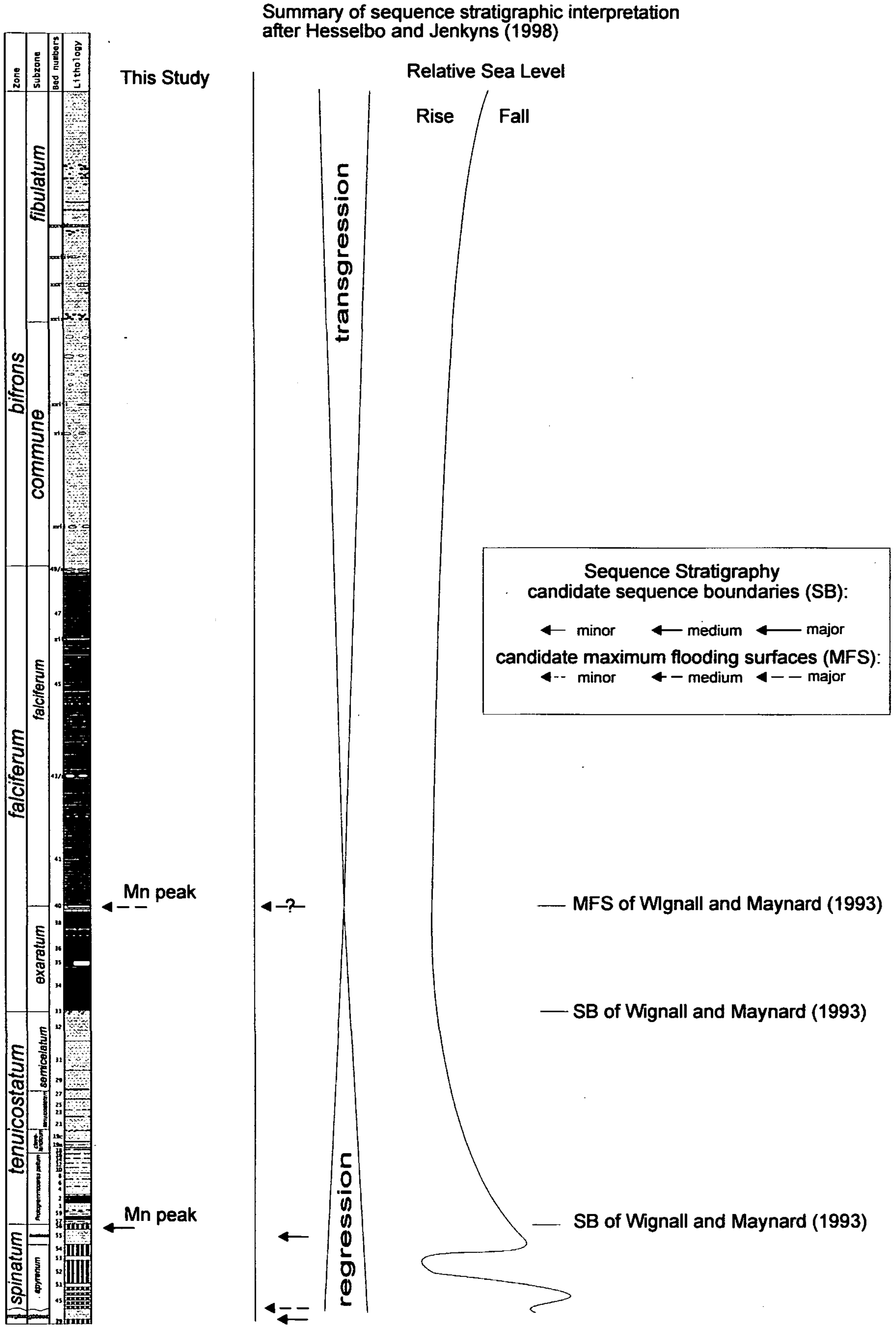


Figure 33. Summary of sequence stratigraphic interpretations for the Upper Pliensbachian - Lower Toarcian of the Cleveland Basin, Yorkshire and proposed sea-level curve after Hesselbo and Jenkyns (1998).

Ba maxima could therefore be interpreted as short term pulses of increased fertility. Evidence for sea floor anoxia, leading to black shale deposition corresponds to periods of enhanced fertility of surface waters. A high faecal pellet flux has been documented during phytoplankton blooms in modern oceans (e.g., Porter, 1984). Increases in faecal pellets in sedimentary successions has also been inferred to represent high productivity events (e.g., Leithold, 1993; Sethi and Leithold, 1994; Bellanca *et al.*, 1999). As the observed Ba peaks are not synchronous with Ca, this could infer that black shale formation is productivity driven rather than by other mechanisms such as preservation.

The hypothesis that black shales are generated by deposition under anoxic water columns continues to be a controversial subject (Pedersen & Calvert, 1990; Arthur & Sageman, 1994; Wignall, 1994). Disagreement on the origin of modern organic-rich sediments centres on the relative importance of primary productivity (organic carbon flux) versus possible preservational mechanisms such as water-column anoxia and sedimentation in particular. The continuing debate about ancient black shales stems from the "no-analogue" global environment that exists at present and the insufficient stratigraphic, sedimentological and geochemical data for black shales form resolving accumulation rates and definitive indicators of productivity and anoxia, among other parameters (Arthur & Sageman, 1994; Wignall, 1994).

The simple presence of anoxia is not thought to foster burial of organic-rich sediments. Indeed recent research has shown that in rapidly accumulating deposits, anaerobic bacterial metabolism is as quantitatively important to degradation or organic material as aerobic decomposition (e.g., Martens & Klump, 1984; Kristensen & Blackburn, 1987). According to Pedersen & Calvert (1990), the key to black shale formation lies in the input flux of organic matter to the sediments and not to the redox status of the depositional basin.

Jenkyns (1988) proposed two tentative models for the explanation of the Early Toarcian bituminous sediments. One model requires high organic productivity and generation of an oxygen minimum zone which extends into the open ocean. In the second model only moderate organic productivity is assumed and the deposition of organic-rich sediments is primarily due to enhanced preservation resulting from a delta-derived freshwater lens. Since the German Posidonienschiefer was deposited in a shallow epicontinental sea, Brumsack (1991) suggests that a distinct fluvial influence is not unlikely. Water column stagnation may then have resulted from restricted oxygenation of the deeper waters because brackish and possibly oxic surface waters overly more saline, anoxic waters. Brumsack (1991) believes that these conditions did at least exist during deposition of the bituminous layers and, for a longer time interval, during the *exaratum* to *falciferum* Subzones. Conversely, while models for the Toarcian black shales remain largely speculative, Jenkyns (1988) favours upwelling and increased planktonic productivity, commencing in pre-Toarcian time, for the *falciferum* Zone event. Farrimond *et al.* (1989) found that geochemical data from the Southern Alps region of Italy (Tethyan margin) do not agree with a scenario of high surface productivity coupled with a largely oxygen-poor water column. Rather, they suggest oxic conditions at intermediate water depths, with anoxia begin restricted to the basin bottoms and a possible oxygen-minimum layer in the upper part of the water column. In the Paris Basin (of the northern epicontinental seas), Farrimond *et al.*, (1989) propose that salinity stratification may have been a significant local influence upon black shale deposition in parts of both the shelf seas and the ocean margin during the Toarcian Oceanic Anoxic Event.

Given the varying interpretations of the effects and causes of black shale events, it is not unreasonable to assume that the many regional differences may actually be linked with

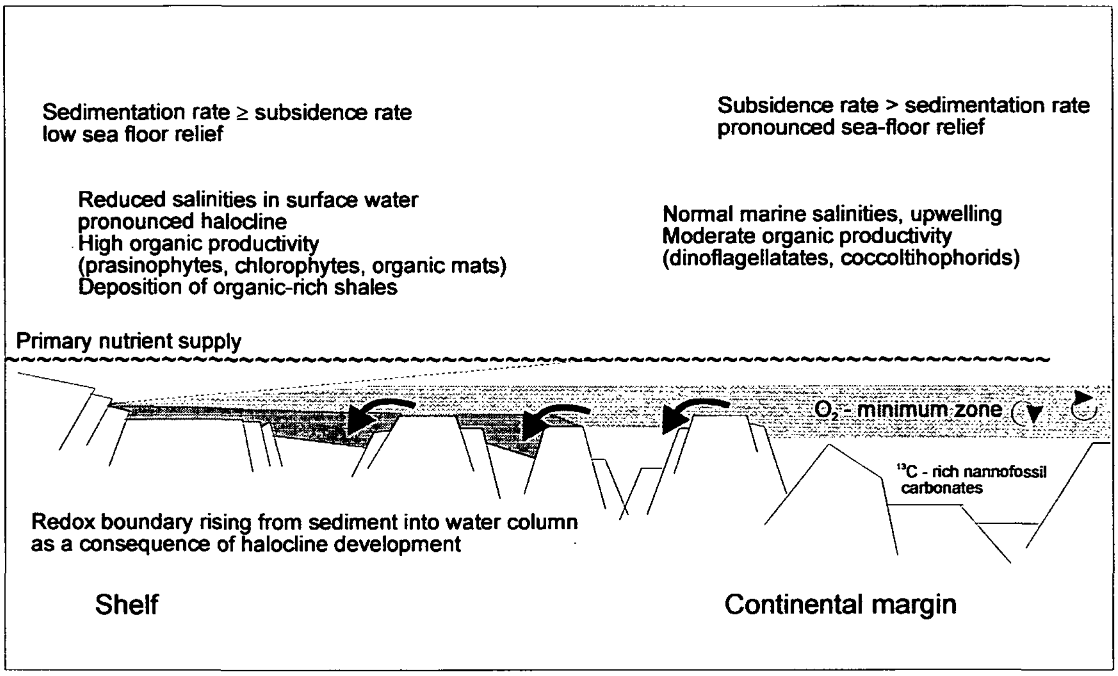


Figure 34. Model showing suggested relation between Posidonienschiefer formation and ocean margin conditions (after Riegel et al., 1986).

broader oceanic conditions and consequently correlated with facies in other regions, attributable to a common global event. The model proposed by Riegel *et al.* (1986), to explain black shale formation in the Toarcian of north west Germany, invokes a major turnover in phytoplankton assemblages interpreted as a response to lowered salinities in surface waters of the epicontinental sea. This model, summarised in Figure 34 shows a suggested relation between regional black shale formation and ocean margin conditions.

The suggestion of different depositional models in different regions does not necessarily question the true global character of the Toarcian oceanic anoxic event. Local environmental factors apparently influenced black shale deposition (Jenkyns, 1985, 1988; Farrimond *et al.*, 1989), although it is likely that the coincidence of several global factors favoured organic-rich sediment accumulation during the Toarcian. These, and other outstanding questions and uncertainties concerning the Toarcian Oceanic Anoxic Event, demand further investigations to address the problem of organic matter productivity *versus* preservation.

5.7 Summary and Conclusions

The approach taken in this study, aimed to extract as much palaeoenvironmental information as possible from the sample sets, characterised the microfacies in order to determine:

- the presence or absence of benthic microfauna in samples that could not be disagregated using available techniques, using thin-section examination,
- palaeoenvironmental data where foraminiferal evidence was lacking, especially critical during peak anoxic conditions,

- the relationship between trace elements and the development of anoxic conditions and changes in sea-level.

Microfacies: Yorkshire, Dotternhausen and Truc de Balduc

The results of this study would seem to indicate that the laminations, rather than reflecting annual changes in sedimentation, actually represent fluctuations in rates of primary production (carbonate and organic matter) and clastic background sedimentation. The type and degree of lamination is directly controlled by the rate of deposition and physical form of the organic matter. The vertical progression from indistinct laminations, through the development of organic rich laminations and the return to indistinctly laminated mudstones is interpreted here to be a result of the changes in sedimentary processes. A sequence, from the initial dominance of bottom current action, to activity by benthic microbial mats, to suspension settling in deeper offshore water is proposed. The primary lamination types can be modified by the occurrence of organic matter, and therefore, can indicate the recovery from the low oxygen conditions.

Pyrite Analysis: Yorkshire Coast

The size distribution of the pyrite framboids and lamination type has also been characterised in order to reconstruct the oxygenation history together with evaluating environmental change. Within the well laminated organic rich microfacies (Jet Rock *s.s.* and lower Bituminous Shales) framboidal pyrite is dominant and ranges in size from 1-12μm. This narrow size range may reflect relatively short growth times, suggesting that most pyrite in these units formed near the sediment/water interface. Within the less restricted microfacies (Grey Shale and Alum Shale Member) pyrite framboids have a greater size distribution and other fabrics form, including large pyritic masses replacing shell fragments and burrow infills.

Trace Element Analysis: Yorkshire Coast

Mn, in carbonate dominant sequences, has been considered to be a robust indicator of sea-level change, increases of Mn being associated with condensed sequences and maximum flooding surfaces. Although the significance of Mn within mudstone dominated sequences is less clear, Mn-rich carbonates are widely observed in Lower Toarcian anoxic carbon-rich deposits from Europe. Minimum Al values (indicative of reduced clay input) and maxima of Ca and Mn at the base of the *falciferum* Subzone may be an artifact of condensation of carbonate material possibly due to sediment starvation and correspond to published estimates of a maximum flooding surface (e.g., Wignall and Maynard, 1993, but see also Hesselbo and Jenkyns, 1998). The increases in Ba are interpreted as short term pulses of increased fertility. The observed Ba peaks are not synchronous with Ca which may indicate that black shale deposition is productivity driven.

Chapter 6 Foraminiferal Palaeoecology

6.1 Introduction

Palaeoecological interpretations of Jurassic foraminiferal assemblages are frequently problematic because of the lack of direct Recent analogues. This is due to the drastic changes which took place in benthic shelf assemblages during the Cretaceous and Tertiary (Copestake and Johnson, 1989). These changes resulted in the replacement of nodosariids, which were dominant in the Jurassic (Gordon, 1970), by other families of the Rotaliina. It has been also established that nodosariids, in the modern day, occupy a deeper water setting than in the Jurassic (Johnson, 1976).

It is widely accepted that the Jurassic sediments of northern and central Europe were deposited in an extensive shallow epicontinental sea of a type which does not exist today (Hallam, 1998). It was characterised by extremely low slopes over large areas, facies belts of vast extent, dampened tidal range (Riegraf, 1985), few sediment gravity flows and extensive storm influence (Hallam, 1981b; Sellwood, 1986). Depths of a few tens of metres are the most probable (Hallam, 1975; Riegraf, 1985;). Most interpretations based on sedimentological criteria (e.g., Hesselbo and Jenkyns, 1998) are supported by palaeontological data for which Hallam (1989) cites bivalves and brachiopods as the two most important Jurassic groups. Indeed, palaeontological data frequently provide a far more sensitive gauge of relative water depth, or even absolute depths, than do sedimentological features (Brett, 1998).

However, the determination of water depth remains a difficult challenge although a significant advance might be possible using foraminiferal data. The application of foraminiferal data to the interpretation of palaeobathymetry makes use of the predictable recurrence of particular benthic biofacies with depth zones. This approach, pioneered by Ziegler (1965), has proven to be applicable to foraminiferal studies of the Lower Jurassic.

6.2 Early Jurassic foraminifera as sea-level indicators

Within nodosariid-dominated populations, major variations in specific and generic abundance are seen in taxa which are long-ranging, suggesting an environmental control (Copestake and Johnson, 1989). The statistical relationships between foraminiferal assemblages and depositional environment have been explored by Brouwer (1969), Johnson (1975) and Muller (1990). The three main studies are summarised in Sections 6.2.1 - 6.2.3. The earliest study by Brouwer (1969) examined assemblages from N. W. Europe while more recently Muller (1990) used statistical analysis of foraminiferal assemblages from the UK Lower Jurassic to propose 'biofacies' groups and hence a depth distribution model.

The foraminiferal assemblages of the Lower Jurassic of northwest Europe are characterised by combinations of a restricted number of species which constitute the bulk of the fauna. Illustrated in Figure 35, the elongate, flattened *Astacolus*, the uniserial, ribbed groups of *Lingulina tenera*, *Frondicularia* and *Marginulina* dominate these smaller benthic foraminiferal assemblages.

Also present are a number of species of the long ranging genera *Lenticulina* and *Nodosaria*. These species can be considered as to be the principal components of the assemblages. While Lower Jurassic assemblages are dominated by the Suborder Lagenina, certain combinations of the principal faunal components appear repeatedly.

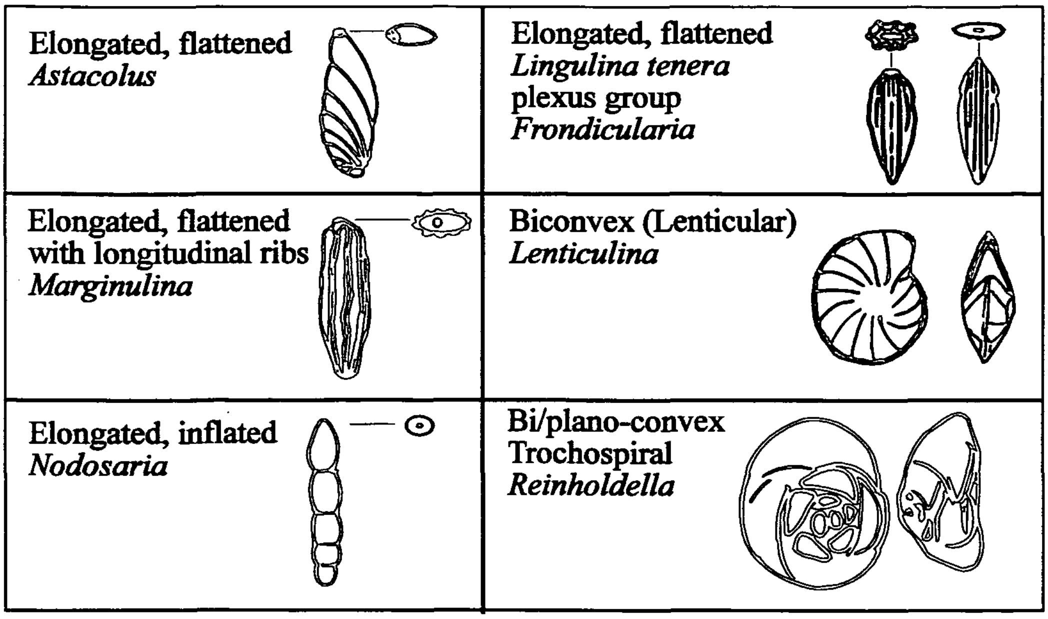


Figure 35. Palaeoenvironmentally significant morphologies in Lower Jurassic assemblages of NW Europe.

Within this limited fauna, certain associations, found repeatedly in the successions, are replaced by other combinations. In the change from one environment to another, one or more of the principal components are usually replaced by others. Therefore, different environments of deposition result in different combinations of principal components.

6.2.1 Brouwer's (1969) Assemblage Model

Brouwer (1969) established a series of species trends for the Lower Jurassic of northwestern Europe, which were thought to reflect a range of environments: deepest and/or most open marine conditions; open-marine, near-shore conditions; and shallowest marine or brackish-water conditions. Using matrix-analysis, Brouwer identified twenty-one foraminiferal assemblages in the Lower Jurassic of northwestern Europe. He proposed a model for faunal succession from shallow to deep or open marine conditions and this is illustrated in Figure 36. In this model, for example, the *Eoguttulina liassica* assemblage is indicative of a shallow or brackish-water environment. At the other extreme, Brouwer suggested that deeper, shelf environments were dominated by *Lenticulina* (including *L. muensteri* and *L. varians*), intermediate depths by the *Marginulina prima* plexus and shallower, shelf depths by the *Lingulina tenera* plexus. However, while Brouwer's analysis clearly indicated that distinctive assemblages exist within the overall nodosariid-dominated shelf areas, he presented little direct evidence to support his environmental interpretations.

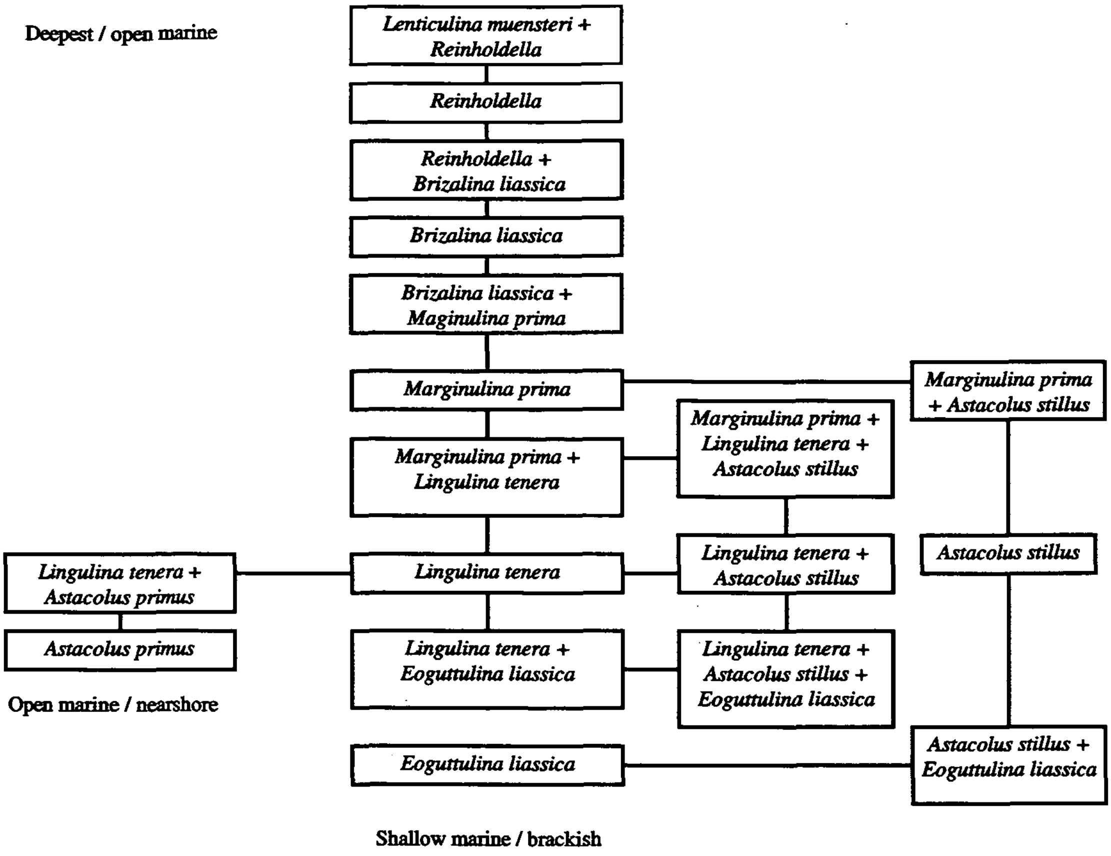


Figure 36. Brouwer's (1969) succession of foraminiferal assemblages. Brouwer originally used Lenticulina gottingensis which in this study is considered synonymous with Lenticulina muensteri.

6.2.2 Ecological Ranges of Johnson (1976)

Johnson (1976) established palaeoecological data on individual benthic foraminiferal species from the Lower Jurassic section of the Llanbedr (Mochras Farm) borehole, North Wales. The interpreted ranges are broad, varying between the inner and outer shelf, although in some instances it was possible to refine the environmental interpretations in terms of depth or oceanic circulation.

One of the problems of considering diversity variations solely as a function of depth is illustrated by the data established for *Reinholdella dreheri*. This species was interpreted by

Brouwer (1969) as being an open and/or deep-water marine indicator. Johnson (1975), however, showed it to have had broad environmental tolerances and to have ranged between the inner and outer shelf (See Table 8). At Mochras it seems to have reached its greatest abundance in the deeper waters of the *falciferum* Zone, where diversity values are very low. As the *falciferum* Zone was a period of widespread marine stagnation and restricted ocean circulation, the primary parameter controlling distribution of *R. dreheri* is probably oceanic circulation and not depth.

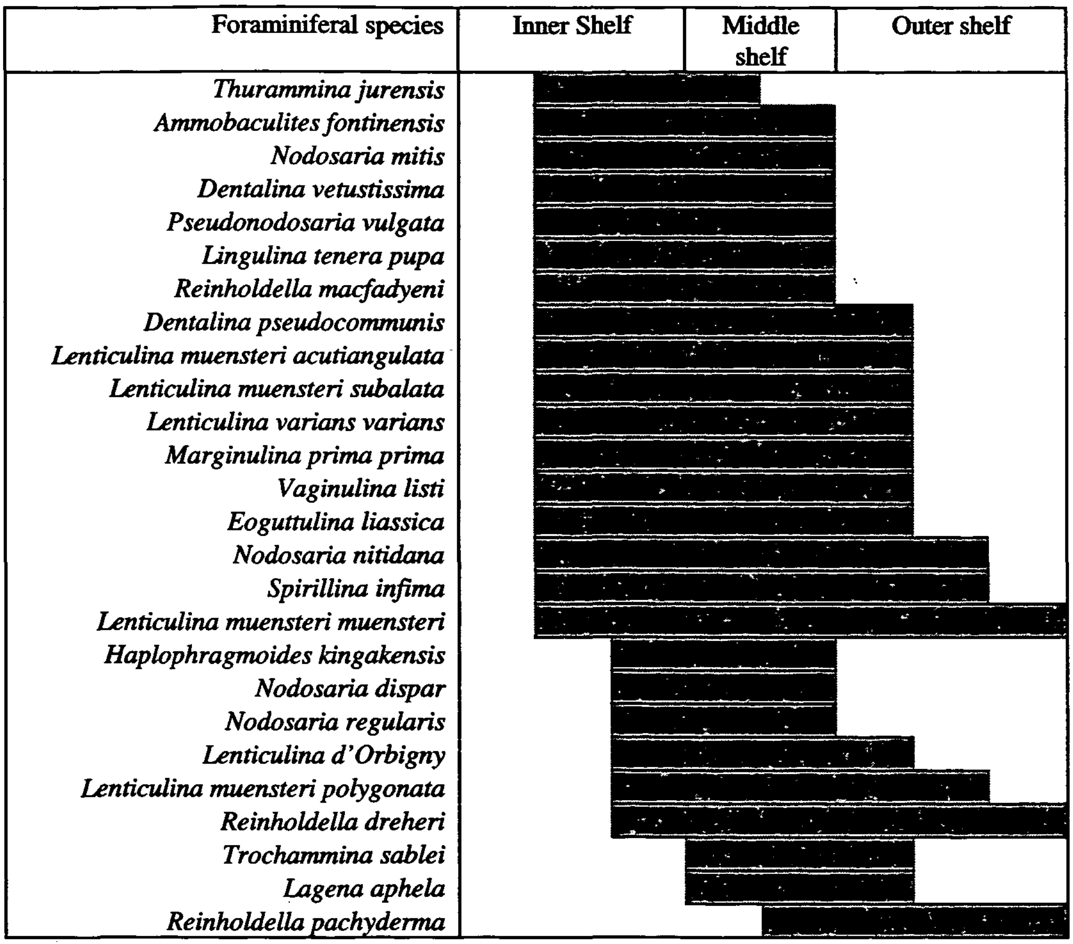


Table 8. Interpreted environmental (shelf) range of selected foraminiferal species after Johnson (1976).

It was suggested by Barnard (1956) that certain trends produced during the evolution of a plexus might be due to changes in the environment. This suggestion is supported by the palaeoenvironmental data established by Johnson (1976) on the different members of the various plexi recovered from the Mochras succession. Table 8 shows that the interpreted ranges of the members of the *Lenticulina muensteri* plexus and the *L. varians* plexus are broadly similar. Any slight differences are attributed to minor variations in broad environmental preference or to variations in the micro-niche occupied within the same broad environmental range. However, the interpreted environmental ranges of the plexi recovered indicate that each member occupied a slightly different environmental range.

6.2.3 Muller's (1989) Foraminiferal Biofacies

Muller (1989) identified thirteen discrete benthic foraminiferal groups by Q-mode cluster and factor analysis in the Lower Jurassic of the United Kingdom. The thirteen groupings were designated as biofacies and Muller proposed a model of Lower Jurassic benthic foraminiferal palaeobathymetry ranging from very near shore to outer shelf or shelf basin.

Shallow water, lagoonal or shoreline environments are indicated by Biofacies Alpha and Alpha 1. Biofacies Alpha, which is dominated by *Eoguttulina* and *Lenticulina,* suggests a palaeodepth of only a few metres. Biofacies Alpha 1, an arenaceous-rich biofacies, apparently lived within the influence of wave action.

Inner shelf environments are indicated by Biofacies Beta, Gamma and Gamma 1. All three biofacies contain an important *Lingulina tenera* component. Biofacies Beta is completely dominated by this species, while Biofacies Gamma and Gamma 1 have greater diversity and equitability. The latter biofacies is dominated by *Brizalina liassica*; whereas *Lingulina tenera* is the second most prevalent species.

Biofacies Delta is interpreted as indicating transitional inner shelf to middle shelf environments. *Lingulina tenera* and *Marginulina prima* are, respectively, the dominant and subordinate species. In the middle shelf, Biofacies Delta through Iota, the trend of dominance of the species *Lingulina tenera* declines and other species become more prominent.

In Biofacies Epsilon, *Marginulina prima* is the dominant species. *Lenticulina varians* and *Astacolus pauperatus* increase in Biofacies Zeta and *Spirillina infima* in the most abundant species in Biofacies Eta and Theta.

Biofacies Iota, which is characterised by the species *Lenticulina varians* and *Lenticulina muensteri,* is interpreted as indicating transitional middle to outer shelf environments. *Spirillina infima* is less abundant in this biofacies.

Outer shelf environments are suggested by Biofacies Kappa, which is dominated by the genus *Opthalmidium,* while the declining trend of the species *Spirillina infima* continues in this biofacies. Outer shelf, or shelf basin, conditions are indicated by Biofacies Lamda which is dominated by the species *Reinholdella macfadyeni* and *Lenticulina muensteri. Lingulina tenera* is an important accessory species. This biofacies is prevalent in the Lower Toarcian, an interval in which many authors propose a significant transgression (Hallam, 1981; Haq *et al.,* 1987; Hesselbo & Jenkyns, 1998).

Cycles of sea-level change suggested by the faunal successions of this model are generally similar to the curves for sea-level change of Hallam (1978) and Vail *et al.*, (1984).

6.2.4 Foraminiferal assemblage model

Occasionally the subordinate groups become dominant over nodosariids and intervals mainly represented by *Spirillina* and *Opthalmidium* can occasionally occur. Gordon (1970) has interpreted such floods as indicative of shallowing, however, in the case of *Opthalmidium* the reverse would appear to be true. Data on *O. macfadyeni* and *O. liassica* compiled during this study and from the Oxford Clay - Corallian succession of the Dorset Coast (Oxford *et al.,* in press) show peak abundances adjacent to maximum flooding surfaces. It appears, therefore, that such occurrences are related to transgressive events, rather than as an indication of shallowing.

A further complication occurs with aragonitic taxa, such as *Reinholdella*, that *are* more abundant in clays and appear to be deeper marine. The question arises as to whether this is the original distribution or a remnant distribution because aragonite does not survive in any other lithology? Henderson & Hart (2000) find that in the Oxfordian of North Dorset, the aragonitic epistominids tend to be preserved in clay-rich sediments and may, therefore, appear to be concentrated adjacent to maximum flooding surfaces. In this case, however, certain "events" recorded within the north Dorset sequences are correlatable with maximum flooding surfaces recorded in the North Sea Basin, despite the distances between basins.

Polymorphinids (mainly represented by *Eoguttulina liassica*) occasionally occur in abundance. It is known that this species thrived in Rhaetian hyposaline carbonates (such as the White Lias) and it may, therefore, also indicate environments which deviated from normal salinity in the Early Jurassic. Brouwer (1969) also considered the species to be a possible indicator of lagoonal or shallow marine environments, based on analogy with modern day *Guttulina* distributions.

The genus *Reinholdella* frequently occurs in abundance at certain intervals in the Lower Jurassic but has been difficult to interpret palaeoenvironmentally (Copestake and Johnson, 1989). Overall facies evidence suggests that levels of increased abundance may be associated with transgressions; e.g., the abundance of *R. macfadyeni*, *R. dreheri* and *R. pachyderma* in the *tenuicostatum - bifrons* Zones. This appears to agree with Brouwer's (1969) interpretation of the genus as a deep-water indicator in the Lower Jurassic.

There are, however, suggestions that individual species within the genus had different environmental preferences (Copestake and Johnson, 1989). Abundant *R.? planiconvexa* is not normally associated with diverse nodosariid populations whereas *R. macfadyeni* and *R. pachyderma* occur with rich diverse nodosariid assemblages; e.g., in the *tenuicostatum*

Zone. It is, therefore, likely that the abundance of *R.? planiconvexa* may have been a response to lowered oxygen levels.

The above examples illustrate that benthic foraminiferal distributions are regulated by the interplay of organic flux, oxygen and competition (Van der Zwaan *et al.*, 1999). Benthic foraminifera, as most microbiota, are not stenotopic to most environmental variables. A more generalist strategy seems beneficial since a low degree of specialisation prevents rapid extinction. Species distribution with depth is, therefore, considered to be mainly a function of organic flux and oxygenation (see Figure 37). In order to take account of these factors, palaeobathymetry should not be based on individual marker species, but preferably on quantitative assemblage characteristics. Van der Zwaan *et al.* (1999) suggest that benthic foraminifera could be attracted selectively to certain bacteria as a source of food. In that way the infaunal position could not be only the consequence of adaption to a certain redox level and decreased competitional pressure, but also the result of stratified occurrence, and areal distribution, of specific bacterial food. Recent research has shown that, in Recent foraminifera, apertural shape (a specific characteristic in modern faunas) is a function of the shape of symbiotic bacteria in different environments (Manley, 1997).

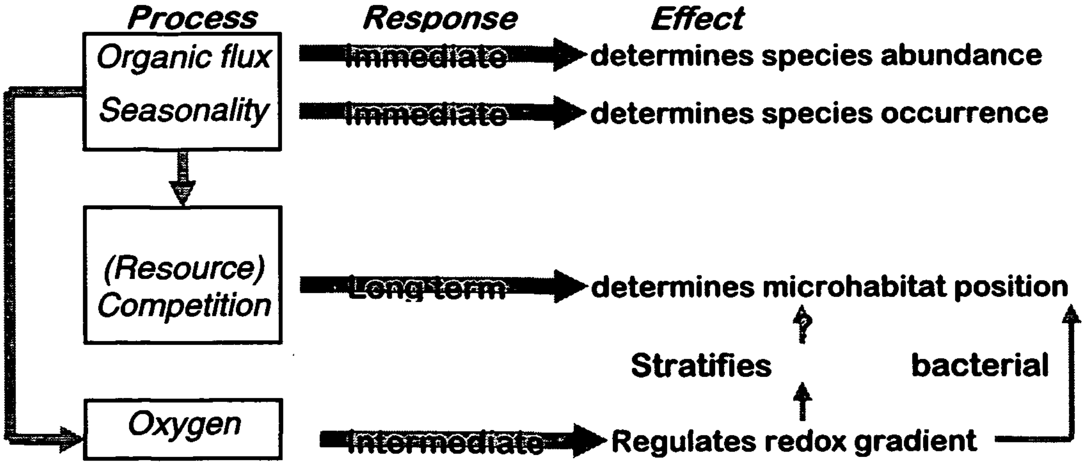
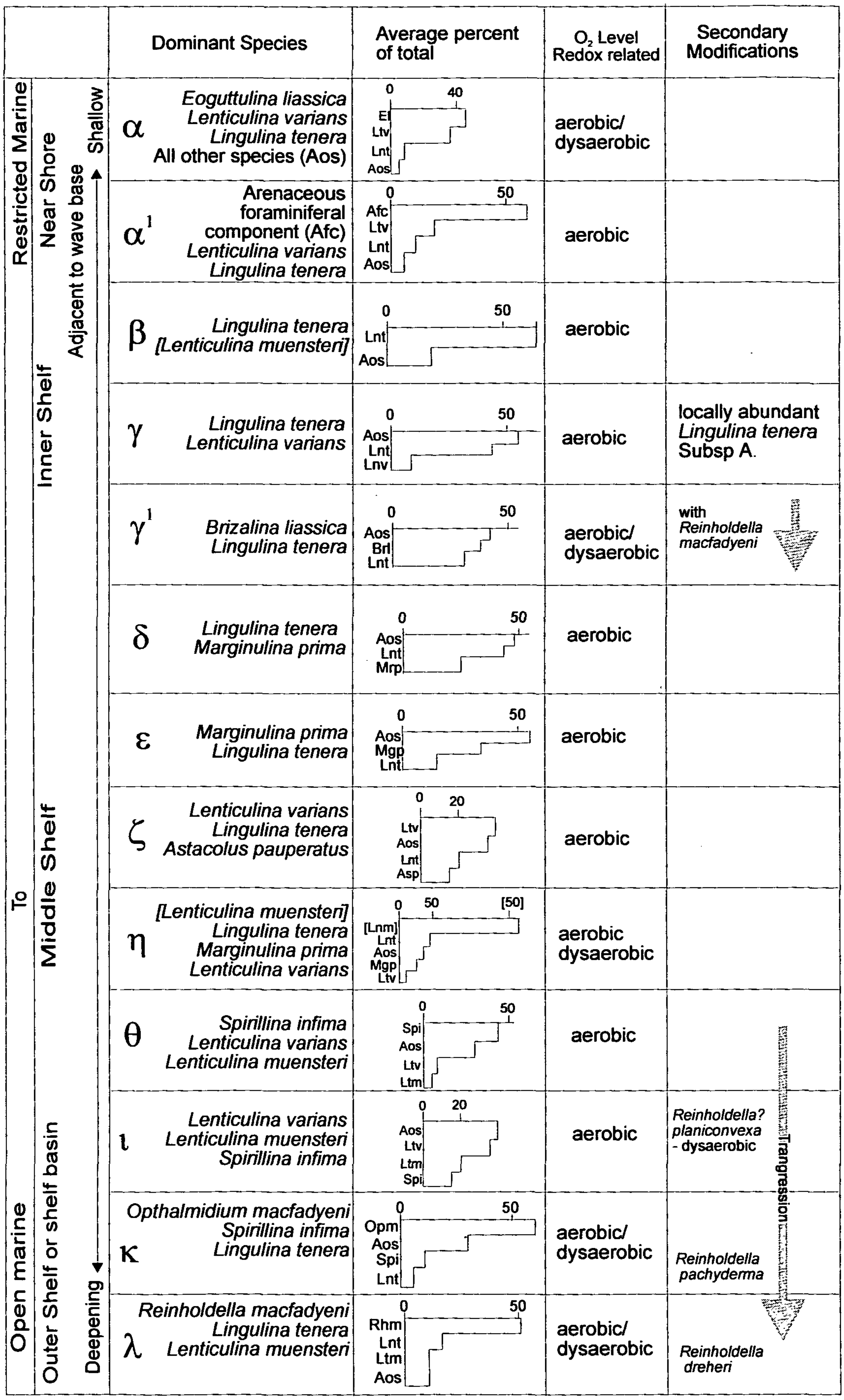


Figure 37. Overview of the most important processes affecting benthic foraminiferal distribution (after Van der Zwaan et al., 1999).

Consequently, considerable care needs to be exercised when considering benthic foraminifera as proxies for relative sea-level. The model proposed in Figure 38 uses Muller's (1990) biofacies groupings (first three columns) modified by the findings of Brouwer (1969), Johnson (1976) and the author (last two columns). The histograms define the biofacies in terms of the predominant species in the assemblages.

The environmental ranges of certain plexus members can be used to complement the statistical correlations of Muller (1990). For instance Johnson (1976) shows that *Reinholdella macfadyeni* ranges between the inner to middle shelf while *Reinholdella pachyderma* ranges from the middle to outer shelf.

Muller's (1990) biofacies model has an interesting feature in that it takes no account of extinction and faunal replacement in the post-*falciferum* Zone. Although the precise details of this replacement are discussed later in this chapter (see Section 6.4), the model (Figure 38) has been modified to take into account the dominance of the *Lenticulina muensteri* plexus group.



	Dominant Species	Average percent of total	O_2 Level Redox related	Secondary Modifications
α	*Eoguttulina liassica* *Lenticulina varians* *Lingulina tenera* All other species (Aos)	0 40 El Ltv Lnt Aos	aerobic/ dysaerobic	
α^1	Arenaceous foraminiferal component (Afc) *Lenticulina varians* *Lingulina tenera*	0 50 Afc Ltv Lnt Aos	aerobic	
β	*Lingulina tenera* *[Lenticulina muensteri]*	0 50 Lnt Aos	aerobic	
γ	*Lingulina tenera* *Lenticulina varians*	0 50 Aos Lnt Lnv	aerobic	locally abundant *Lingulina tenera* Subsp A.
γ^1	*Brizalina liassica* *Lingulina tenera*	0 50 Aos Brl Lnt	aerobic/ dysaerobic	with *Reinholdella macfadyeni*
δ	*Lingulina tenera* *Marginulina prima*	0 50 Aos Lnt Mrp	aerobic	
ε	*Marginulina prima* *Lingulina tenera*	0 50 Aos Mgp Lnt	aerobic	
ζ	*Lenticulina varians* *Lingulina tenera* *Astacolus pauperatus*	0 20 Ltv Aos Lnt Asp	aerobic	
η	*[Lenticulina muensteri]* *Lingulina tenera* *Marginulina prima* *Lenticulina varians*	0 50 [50] [Lnm] Lnt Aos Mgp Ltv	aerobic dysaerobic	
θ	*Spirillina infima* *Lenticulina varians* *Lenticulina muensteri*	0 50 Spi Aos Ltv Ltm	aerobic	
ι	*Lenticulina varians* *Lenticulina muensteri* *Spirillina infima*	0 20 Aos Ltv Ltm Spi	aerobic	*Reinholdella? planiconvexa* - dysaerobic
κ	*Opthalmidium macfadyeni* *Spirillina infima* *Lingulina tenera*	0 50 Opm Aos Spi Lnt	aerobic/ dysaerobic	*Reinholdella pachyderma*
λ	*Reinholdella macfadyeni* *Lingulina tenera* *Lenticulina muensteri*	0 50 Rhm Lnt Ltm Aos	aerobic/ dysaerobic	*Reinholdella dreheri*

Figure 38. Foraminiferal assemblage model based upon the thirteen biofacies groupings of Muller (1990), modified with the findings of Brasier (1969) and Johnson (1976). [] indicates post-falciferum Zone replacement species. See text for explanation.

Any faunal study of the Lower Jurassic must also take account of the varying degrees of oxygenation that occur throughout the stages. While peak anoxic conditions were attained in the *exaratum* Subzone of the Toarcian, anoxia developed many times prior to this event. The appearance of widespread bituminous shale horizons mark the beginnings of many transgressive sequences reflecting sea-bed anoxicity during sea-level rise (Hallam and Bradshaw, 1979). The presence of certain foraminiferal assemblages are, therefore, probably indicative of poorly oxygenated conditions. Figure 38 includes a broad interpretation of oxygenation level, which reflects the position of the redox boundary within the sediment or movement into the water column.

The secondary modifications take into account some of the specific occurrences noted during this study. The presence of *Opthalmidium macfadyeni* and species of *Reinholdella* can be used to infer transgressive events and maximum flooding surfaces.

6.2.5.1 Additional palaeobathymetry indicators

Lamination in shales is an important feature useful in providing clues to sedimentary environment (O'Brien, 1990) with variations in types of lamination being related to changes in sedimentary processes. The lamination of the Toarcian Shales of the North Yorkshire Coast, the Schiste Cartons of southern France and the southern German Posidonienschiefer lend themselves to a investigation of sedimentary processes and in particular the depth of water in which they were deposited (Hallam, 1967b; O'Brien, 1990; O'Brien and Slatt, 1990).

Fine lamination is produced in deeper, more offshore anaerobic conditions in which suspension settling dominates. While thick lamination indicates the influence of bottom flowing currents in shallow water. The Toarcian transgressive shale sequence shows a progressive change from thick to wavy to fine lamination relating to progressive changes in the sedimentary processes operating in the environment.

The facies development in the Posidonienschiefer demonstrates a close relationship with the bathymetric development of the available accommodation space where an increase is required in order to permit shale accumulation (Hesselbo and Jenkyns, 1998). Numerous redox parameters and isotope-geochemical indicators (see Röhl, 1988; Schmid-Röhl *et al.*, 1999) correlate with the 3rd order global sea level curve of Haq *et al.* (1988). Röhl (1988) demonstrates a maximum depth during the lower *falciferum* Zone, where quiet water conditions were established in a very flat basin (approx. 80m depth).

It is, therefore, reasonable to assume a basic correlation between microfacies (lamination type) and the depth of water in which the sediments are being deposited in (O'Brien, 1990; O'Brien and Slatt, 1990). Table 9 details the broad correlation between the facies types described in Section 5.3.1 and the foraminiferal biofacies of Figure 38.

Biofacies	Microfacies	Interpreted Environment	
α	NNL	Restricted Marine	
α^1		Near Shore	
β	RIL-RDL		Flow-influenced, off-shore area
χ			[turbidites indicate proximity]
χ^1		Inner Shelf	
δ	BPL-BES		Quiet water, moderate depths
ε			
ϕ		Middle Shelf	
γ	BLS		
θ			
ι			Deep, quiet water conditions
κ	BWY	Open shelf / shelf basin	
λ		Open Marine	

Table 9. Tentative correlation of foraminiferal biofacies α - λ with the microfacies types identified in Section 5.3.1. NNL - normal non-laminated; RIL - restricted indistinctly laminated; RDL - restricted distinctly laminated; BPL - bituminous planar laminated; BES - bituminous elongate streaks; BLS - bituminous lensed; BWY - bituminous wavy.

6.3 Relative sea-level models

6.3.1 Summary models for Pliensbachian - Toarcian sections

The distribution of foraminiferal biofacies, in comparison with other palaeoecological and sedimentological indicators, allows the construction of the models in Figure 39. These sea-level curves can then be compared with those of Hallam (1981a), Haq *et al.* (1987) and also the sequence stratigraphic interpretations of Hesselbo and Jenkyns (1998) and Röhl (1998) for the United Kingdom and Germany respectively.

Hesselbo and Jenkyns (1998) recognise candidate maximum flooding surfaces, identified on the basis of distal starvation, or facies successions indicative of maximal accommodation space in proximal areas, in the *falciferum* - *bifrons* Zones. Candidate sequence boundaries, defined on the basis of major unconformities or facies successions indicative of minimal accommodation space in proximal areas, are recognised in the basal *margaritatus* Zone and *levesequei* Zone. The foraminiferal data generally agree with this pattern for the Dorset and Yorkshire sections (Figure 39c and d).

The relative sea-level curves for Dotternhausen and Truc de Balduc (Figure 39a and b) display many similarities with the curves of Hallam (1981a) and Haq *et al.* (1987). Both of the curves determined on the basis of the foraminiferal data show a transgressive event across the *spinatum-tenuicostatum* Zone boundary followed by a minor regression, before a rise in sea-level into the *falciferum* Zone and the peak anoxia.

The deepening phase appears to last longer at Dotternhausen than at Truc de Balduc, where the foraminiferal assemblages indicate a rapid drop back to *tenuicostatum* Zone levels. However, Truc de Balduc shows more similarity with the Cleveland Basin as both indicate

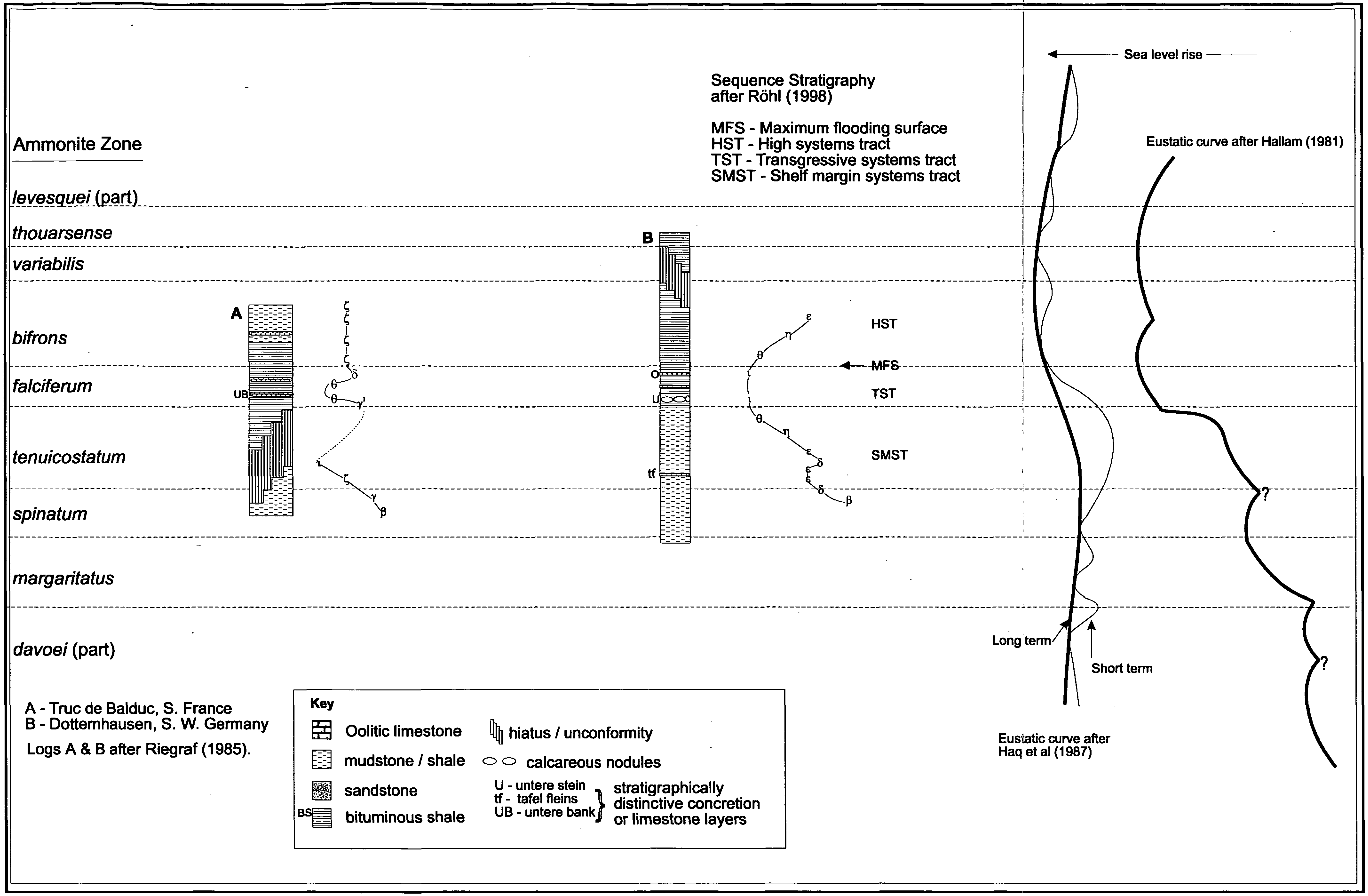


Figure 39. Relative sea-level during the Pliensbachian to Toarcian of NW Europe determined on foraminiferal biofacies and microfacies occurrences. For explanation of Biofacies see Fig. 38. Those in light type are determined from microfacies analysis (Table 9).

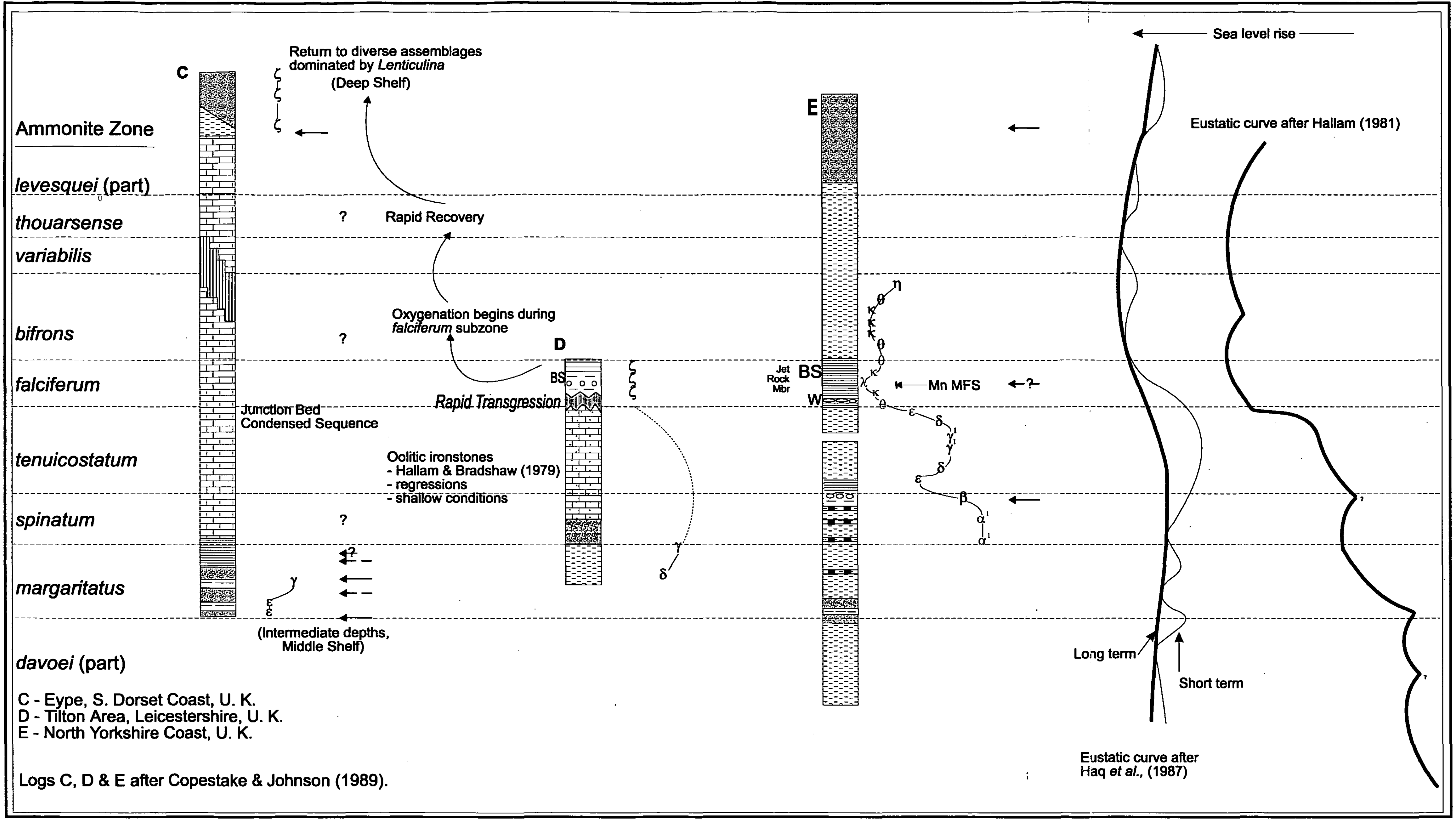


Figure 39 continued. Relative sea-level during the Pliensbachian to Toarcian of NW Europe determined on foraminiferal biofacies and microfacies occurrences. For explanation of Biofacies see Fig. 38. Those in light type are determined from microfacies analysis (Table 9).

Sequence Stratigraphy
after Hesselbo and Jenkyns, 1998

candidate sequence boundaries (SB):

← minor ←— medium ←—— major

candidate maximum flooding surfaces (MFS):

←-- minor ←_ medium ←— — major

Key

- ▦ Oolitic limestone
- ▤ mudstone / shale
- ▩ sandstone
- BS ☰ bituminous shale
- ▥ hiatus / unconformity
- ○○ calcareous nodules
- w-Whalestone } stratigraphically distinctive concretion or limestone layers
- Mn - Manganese

a rapid transgression in the early *tenuicostatum* Zone followed by a minor regression before the major transgressive phase peaking in the *falciferum* Zone. Truc de Balduc exhibits a hiatus in this interval which could be attributed to sediment starvation and condensation at the maximum flooding surface, reflecting a more distal location than that of the Junction Bed of the south Dorset coast. The foraminiferal curves also agree with the sequence stratigraphic interpretation of Röhl (1998), that was based upon macro-palaeontological and geochemical interpretations. Palaeobathymetric interpretations of the microfacies (Table 9) complement the foraminiferal data and constitute a useful proxy in the absence of a microfauna.

6.3.2 Palaeoenvironments at East Quantoxhead

By early Hettangian times a broad shallow marine shelf sea was established over most of Britain and north-west Europe, colonised by a low (but gradually increasing) diversity foraminiferal fauna. Imposed upon this general trend of sea-level rise, with major pulses in the early Hettangian and early Sinemurian, were episodic falls of sea-level (Hallam, 1981a).

Changes in foraminiferal assemblages are seen to be related to sea-level changes, in that well-documented transgressions mark the arrival of new species and subspecies (evolutionary appearances and/or migration) whereas regressions and times of lowered sea-level appear to equate to extinctions (Copestake & Johnson, 1981). Accordingly the foraminiferal data in Figure 25 can be used, in conjunction with published depth distributions (Figure 38), to construct a model of environmental change across the Hettangian - Sinemurian boundary at East Quantoxhead. The model in Figure 40 can then

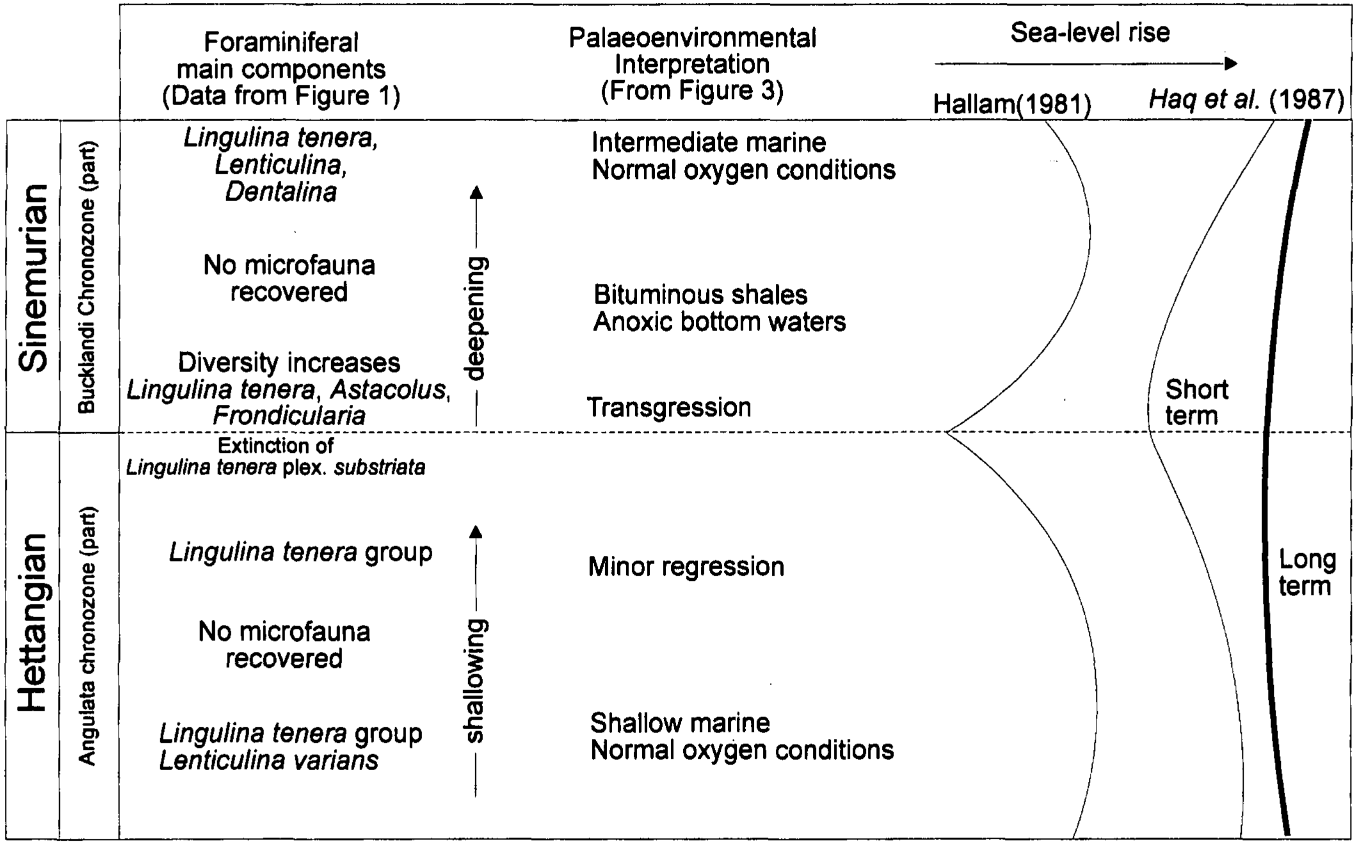


Figure 40. Interpretation of eustatic events and palaeoenvironments from foraminiferal evidence at East Quantoxhead. CMFS - Candidate maximum flooding surface; CSB - Candidate sequence boundary (after Hesselbo and Jenkyns, 1988).

be compared with published sea-level curves of Hallam (1981a) and Haq *et al.* (1987) and the sequence stratigraphic interpretation of Hesselbo and Jenkyns (1989).

Hallam (1978) records a basal Sinemurian (early *bucklandi* Zone) transgression, preceded by a late Hettangian regression. However, this event is only apparent in Europe where, for example, sandstones are abruptly replaced by marls and limestones, in NE France and southern Germany. The Blue Lias facies of southern England, however, continues across the stage boundary with only subtle changes. Hallam (1981a) suggests, therefore, that if any eustatic event took place at all, it must have been only a minor event.

Subtle changes in the foraminiferal assemblages at East Quantoxhead would seem to support the case for a minor eustatic event. Within these nodosariid-dominated foraminiferal populations, major variations in species and generic abundances are seen in taxa which are long ranging, suggesting controlling palaeoenvironmental factors. The predominance of the *Lingulina tenera* (Bornemann) plexus with associated *Lenticulina* and *Marginulina* species in the lower part of the section suggests inner to near shelf environments with periods of normal oxygen levels.

Towards the Hettangian/Sinemurian boundary, there is a noticeable decline in abundances and diversity, eventually resulting in the extinction of *Lingulina tenera* plex. *substriata.* If extinctions are assumed to be indicative of a regressive phase, Copestake & Johnson (1989) also report that several index foraminifera disappear at, or near, the top of the *angulata* Zone at many European localities (*Lingulina tenera collenoti*, *L. tenera substriata*, *Frondicularia terquemi* subsp. A) while *Dentalina langi* both appears and becomes extinct within the late *angulata* Zone. An increase in diversity across the boundary indicates a return to deeper, oxygenated conditions, reflecting a transgressive event. The higher levels of the section contain darker, more organic rich marls and shales representing low-oxygen bottom water conditions that lack any benthic fauna, including foraminifera.

In a study of the Blue Lias of southern Britain, Weedon (1986) proposes a hemipelagic shelf regime being supplied with clay from rivers. The cycles in bottom-water oxygenation, which affected organic carbon contents, were associated with changes in the clay-to-carbonate mud ratio. These changes are ultimately believed to be caused by climatic cycles changing sedimentation rates and indirectly affecting primary productivity through increases of nutrients in runoff water. The anoxic conditions may then have resulted from the additional organic matter removing oxygen through decay, leaving an organic excess. Bottom-water anoxia and increased clay supply will affect benthic assemblages and could be responsible for the barren intervals seen in the foraminiferal and ostracod faunas (Hart and Hylton, 1999).

The ranges of identified foraminiferal taxa at East Quantoxhead have been extended and provide further data to assist in the definition of the base of the Sinemurian stage (Hylton, 1999; Page *et al.,* 2000). These data can be used to interpret the palaeoenvironmental conditions at East Quantoxhead during this interval of the Lower Jurassic.

6.3.3 Palaeoenvironments at Robin Hood's Bay

The low numbers of foraminifera recovered from the Sinemurian - Pliensbachian boundary section prohibit a detailed analysis of the type applied to the other sections in this study; however, some useful palaeoenvironmental inferences can be drawn.

The *raricostatum* Zone has been considered to represent the beginning of a major, latest Sinemurian transgression in Europe and beyond (Hallam, 1961, 1978). In contrast Haq *et al.* (1987) propose a major sea level drop during this Zone. The assemblages of the upper *raricostatum* Zone suggest a middle to inner shelf environment, dominated by *Marginulina* *prima prima* and *Lingulina tenera tenera*. There is a subtle indication of deepening towards the Sinemurian - Pliensbachian boundary with a reduction in the populations of *Lingulina tenera tenera* and an increase in *Lenticulina muensteri muensteri*. This supports the view of Hallam (1981) of a latest Sinemurian transgression.

The Mochras Borehole data, however, show several extinctions at the Sinemurian / Pliensbachian boundary. Copestake and Johnson (1989) propose a possible misinterpretation of shallowing, based on abundances of *Opthalmidium* and *Nubecularia*. Hesselbo and Jenkyns (1998) place a candidate maximum flooding surface at the base of the *jamesoni* Zone while the transition from the Siliceous Shales to the Pyritous Shales is clearly representative of deepening (Hesselbo and Jenkyns, 1995).

6.4 Foraminiferal Response to Low-Oxygen Conditions in the Toarcian of NW Europe

6.4.1 Ecological Strategies

The diverse mechanisms (adaptive traits) for survival through intervals of extinction, proposed by Harries *et al.* (1996) detailed in Section 1.1.1.2 and Figure 2, represent possible explanations for the rapid rate and complex levels of recovery observed in the post-anoxic intervals of the sections studied. Consequently, in addition to the large scale changes in foraminiferal assemblages in response to changing sea-level and environmental conditions, several small scale foraminiferal occurrences have been observed.

6.4.1.1 Characteristic occurrences of benthic foraminiferal taxa

At the base of the *exaratum* Subzone, *falciferum* Zone at Tilton, there suddenly appears an abundance of very small (~100μm diameter) trochospiral foraminifera. Tentatively identified as *Reinholdella? planiconvexa*, they bear morphological and ecological similarities to the aragonitic genus *Conorboides*, which is also reported from the *falciferum* Zone of the Upper Lias at Empingham, Rutland (Horton & Coleman, 1977) and *Oberhauserella quadrilobata* Fuchs, again from the *falciferum* Zone, of the Swiss Alps (Simmons *et al.*, 1997, pl. 2.2, figs 4, 7, 9).

Given their extremely low abundance before the Toarcian event and their 'bloom' once the environmental conditions markedly decline this, taxon could be described as a *disaster* or *opportunist* species as described by Harries *et al.*, (1996). The species dominates after a rapid transgression in the *exaratum* Subzone before the onset of low oxygen conditions and also in the post-anoxic interval.

Similarly, *Reinholdella macfadyeni* occurs in abundance in the *tenuicostatum* Zone of the North Yorkshire Coast. As an indicator of deep water and transgressive events (Brouwer, 1969), *R. macfadyeni* also disappears with the onset of low-oxygen conditions in the Jet Rock *s.s.* only to re-appear as a major contributor to *bifrons* Zone assemblages.

A third species that makes only one, distinctive, appearance is *Lingulina tenera* Subsp A, occurring in the *margaritatus* and *spinatum* Zones of Tilton and Truc de Balduc. At both localities this species is associated with *Lingulina tenera tenera, Lenticulina varians* and members of the *Lenticulina muensteri* plexus. Appearing suddenly at the base of the Upper Pliensbachian and occurring most consistently in the *margaritatus* Zone (Copestake and Johnson, 1989), *Lingulina tenera* Subsp A could be a useful correlative marker across

Europe. The occurrence of this species could be related to the proposed transgressive event at the beginning of the Late Pliensbachian (*margaritatus* Zone).

6.4.1.2 Foraminiferal morphogroups

Previous investigations have indicated that the distribution of foraminiferal morphogroups is strongly related to environmental conditions. Studies have shown that the test shape, mode of coiling, type of aperture and presence or absence of pores reflect different life positions and feeding strategies. Bernhard (1986) suggested that the relative proportions of benthic foraminiferal morphogroups may be influenced by variations in the oxygen and organic carbon content of surficial sediments. Corliss and Chen (1988) found that infaunal morphogroups dominate in areas of increased carbon flux.

Morphogroup analysis has mainly been concerned with modern assemblages. Some studies of functional morphology of modern foraminifera have, however, already been applied to fossil assemblages for palaeoenvironmental interpretation. Studies have been carried out on organic rich sediments from Jurassic through Holocene sections at various locations (Bernhard, 1986), mid-Cretaceous succession in Brazil and England (Koutsoukos and Hart, 1990; Koutsoukos *et al.*, 1990), Palaeogene deposits (Kaiho, 1992), Lower and Middle Jurassic strata of the North Sea deltas (Nagy, 1992), the Upper Jurassic Nupra Formation from Nepal (Holbourn, 1992) and the Middle Jurassic of the Pieniny Klippen Bet, Polish Carpathians (Tyszka, 1994). Table 10 summarises the morphologies and proposed modes of life of palaeoenvironmentally significant foraminifera encountered during this study.

While general in its scope, this study also shows that *Lenticulina,* as the most common genus, must have tolerated a very wide range of environmental conditions from a deep infaunal mode of life to an epifaunal one (Tyszka, 1994). The distribution of the genus is probably related to the depth of the redox boundary within the surficial sediments.

Flattened morphologies, such as those seen in *Frondicularia, Planularia* and some *Lenticulina* species, also predominate in low-oxygen deposits (Bernhard, 1986). While the reason for this is not known it can be seen that these morphologies would reduce the rate of sinking into soft oxygen poor sediments or maximise oxygen uptake (Hendrix, 1958). The discoidal lenticular shape seems to be very efficient on a 'soupy' substrate, providing more surface area per unit volume. This might prevent sinking into a soft, flocculent and anoxic substrate.

Assemblages from the Grey Shale Member of the North Yorkshire coast are dominated by morphogroups C-6 and C-5c. These faunas of *Marginulina prima* (C-5c) and *Brizalina liassica* (C-6) probably composed mobile assemblages of deposit feeders adapted to an infaunal microhabitat in soft, fine-grained, muddy sediments in areas of relative bottom stability and abundant nutrients (in the form of deposited organic detritus).

The recovery of foraminiferal faunas from the Toarcian anoxic events begins to take place during the *falciferum* Subzone, *falciferum* zone. Coiled *Lenticulina* and *Astacolus* appear at Tilton in low diversity late *falciferum* Subzone assemblages, while by *levesquei* Zone times at Eype, the assemblages have returned to pre-event diversity levels and are dominated by *Lenticulina* indicating outer shelf, well oxygenated conditions.

Rhodes and Thayer (1991) note that for bivalves at the Cretaceous/Tertiary boundary extinctions there was selective extinction of suspension feeders and other susceptible trophic categories, relative to deposit feeders and other resistant categories. The predominance of active deposit feeders (i.e., *Lenticulina* and *Astacolus*) during this interval perhaps indicates that this mode of life was an important factor in survival.

Morpho -group		Test form	Life position	Feeding Strategy	Taxa
A-1		Unilocular, discoidal (flattened) coiled	Epifaunal	Active deposit feeders	*Ammodiscus*
A-2		Multilocular, low trochospiral plano-convex or concavo-convex	Epifaunal	Herbivores, detritivors	*Trochammina*
C-1		Conical, low trochospiral	Epifaunal	Active deposit feeder	*Reinholdella*
C-2		Discoidal-flattened (plainspiral) to plano-convex (trochospiral)	Epifaunal	Primary weed fauna, grazing herbivores/detritivores	*Sprillina*
C-3		Discoidal-flattened (planispiral)	Epifaunal	Active deposit feeders, grazing herbivores / detritivores	*Opthalmidium*
C-4		Elongated-flattened	Shallow infaunal	Deposit feeders, grazing omnivores and/or bacterial/detrital scavengers	*Lagena,* *Nodosaria*
C-5	a	Elongated-flattened	Shallow infaunal	Active deposit feeders	*Astacolus* *Planularia*
	b	Elongated-flattened	?Shallow / deep infaunal	Deposit feeders, grazing omnivores	*Lingulina* *Frondicularia* *Vaginulina*
	c	Elongated-flattened with longitudinal elongated ribs	Shallow to deep infaunal	Active deposit feeders, grazing omnivores	*Marginulina*
C-6		Elongate-tapered	Infaunal	Deposit feeders, bacterial and detrital scavengers	*Brizalina*
C-7		Elongated, straight periphery	Shallow to deep infaunal	Deposit feeders, grazing omnivores and/or bacterial/detrital scavengers	*Pseudonodosaria* *Eoguttulina*
C-8		Biconvex (Lenticular)	Epifaunal to deep infaunal	Active deposit feeders, grazing omnivores	*Lenticulina*

Table 10. Selected morphogroup categories of Lower Jurassic benthic foraminifera assemblages, inferred mode of life and feeding habits, after Tyszka (1994) and Koutsoukos and Hart (1990). See Figure 35 for examples of each morphotype.

Pseudonodosaria vulgata (C-7) is also a major contributor to survival assemblages at Tilton, associated with a low number of *Eoguttulina simplex*; both species are deposit feeders or detrital scavengers.

Lenticulina is conspicuously present in almost all of the zones investigated during this study. In certain samples from the Alum Shales of the North Yorkshire Coast, rare *Lenticulina* were associated with infaunal, arenaceous, morphogroups. Arenaceous foraminifera were probably able to tolerate a very low oxygenation level connected with a rather low *p*H within the sediment (Bernhard, 1986; Nagy, 1992). This abundance of arenaceous foraminifera may have been a response to the higher organic influx, which brought about oxygen depletion and low *p*H level in the shelf sediments represented by the Alum Shales.

An increased presence of *Trochammina,* and other arenaceous forms (A-1 and A-2), in the Alum Shales could be interpreted as a response to episodically reduced oxygen concentration and high food availability (Nagy, 1992).

Improved circulation and low organic carbon flux may have brought about a decrease in anoxia and a drop in the redox boundary. Infaunal habitats could then become colonised by shallow infaunal and epifaunal foraminifera such as *Trochammina*, *Nodosaria* and *Reinholdella* as well as the adaptable *Lenticulina.* Small infaunal species (both calcareous and arenaceous) are among the first, and most successful, colonisers of soft bottom habitats from shallow waters to the deep sea (Alve, 1999).

Tyson and Pearson (1991) point out that, with increasing dysoxia, infaunal organisms tend to occupy higher and higher levels within the sediment column, sometimes even taking over niches previously occupied by epifaunal taxa. It seems likely that organisms capable of tolerating a variety of substrates have the greatest potential for survival. In this way, the

Lenticulina populations could have probably tolerated fluctuations in the redox boundary and possessed the ability to migrate vertically within the soft substrate. Deep infaunal, elongated morphogroups would, on the other hand, have been at a disadvantage in the flocculent layer due to their tendency to sink downwards (Tyszka, 1994).

The foraminiferal assemblages from Dotternhausen and Truc de Balduc exhibit many similarities but do not reach the same depths as the Cleveland Basin (North Yorkshire coast). Assemblages from the Dotternhausen quarries show a decrease in abundance across the Pliensbachian - Toarcian boundary with few extinctions (this study; Riegraf, 1985). The main extinction level occurs in the *semicelatum* Subzone of the *tenuicostatum* Zone.

Lenticulina and *Marginulina* dominate Early tenuicostatum Zone assemblages with a minor *Nodosaria* component. Riegraf (1985) reconstructs the depositional environment of the Posidonienschiefer as a shallow large marginal sea with a water depth of about 20 to 50 metres of warm, occasionally hypersaline water. This interpretation is not supported by the foraminiferal evidence, which tends to indicate a deeper setting, although the Dotternhausen curve shows less relative deepening than the other basins. The determination of salinity is more problematic (Hallam, 1998) given the lack of foraminiferal fauna in the most anoxic part of the Posidonienschiefer. However, the assemblages recovered indicate normal marine conditions.

The development of anaerobic conditions reflected in the Posidonienschiefer (*falciferum* zone) resulted in an absence of any benthic foraminifera and diversity does not recover, along with the macrofauna (Little, 1996), until the *bifrons* Zone

One cause of survivorship (and consequent re-population) may be that a population is located beyond the range of extinction processes or due to the broader adaptive ranges of marginal populations (Harries *et al.*, 1996). Species such as *Lenticulina muensteri,* *Lenticulina varians, Astacolus, Eoguttulina* and *Lagenammina* were widely distributed prior to the early Toarcian events and, in addition, displayed a spectrum of morphologies, especially in the case of plexus members. This variation, which Barnard (1956) originally suggested was due to varying environmental conditions, could indeed be attributable to ecophenotypic variation, in response to the varying conditions inhabited by widely dispersed local populations. Environmental changes during an extinction event, such as the expansion of the oxygen-minimum zone during the early Toarcian would result in the extinction of many member of a plexus group, owing to their increased specialisation (see Section 6.2.2). The post-event re-population, in this case, comes from the most 'primitive' form *Lenticulina muensteri muensteri.*

This pattern of *Lenticulina - Dentalina* dominated nodosariid pioneer faunas is seen throughout the Lower Jurassic. Cubaynes and Ruget (1988) propose a Lower Pliensbachian *jamesoni* Zone eustatic transgression that drowned the Quercy platform (northeastern Aquitaine, France). A rapid sedimentation rate characterises the poorer assemblages where, in the deeper environments, *Lenticulina* (73%) dominate the *Nodosaria-Dentalina* associations (21%) with other genera (6%) being poorly represented. However, in the north-west of the region, a relatively slow sedimentation rate (Cubaynes and Ruget, 1988) the populations of *Lenticulina* (28%) seem to be in strong competition with the dentalines (49%) and to a lesser degree with other genera (33%).

6.4.1.3 Size variation in foraminiferal species

A further noticeable trend in foraminifera from low oxygen conditions is towards a reduction in test size. Comparison with Hettangian - Sinemurian assemblages from the UK comprising large *Lenticulina, Lingulina tenera, Nodosaria* and *Marginulina* species (Hylton, 1998) shows a decrease in test size of these genera by the early Toarcian. Having a small test may also maximise relative surface area (Bernhard, 1986). Table 11 compares two species that range from the Hettangian through to the late Toarcian, demonstrating a decrease in test height for elongate species such as *Lingulina tenera*. Small size in benthic foraminifera has been thought to reflect either early reproduction under optimal environmental conditions or dwarfism due to adverse environmental conditions (Boltovskoy and Wright, 1976).

Location / Species	East Quantoxhead, *complanata* Subzone	Tilton, *margaritatus* Zone	Truc de Balduc, *hawskerense* Subzone
Lingulina tenera pupa	800μm	510μm	225μm

	East Quantoxhead, *conybeari* Subzone	Cement Shales, Peak, *fibulatum* Subzone	-
Astacolus / Vaginulinopsis speciosa	750μm	425μm	

Table 11. Comparison of height of test of selected foraminiferal species, through the Lower Jurassic.

Under optimal conditions sexual maturity is achieved early on in ontogeny and individuals reproduce at smaller sizes (Bradshaw, 1961). Small individuals consume less oxygen than larger individuals (Bradshaw, 1961). Phleger and Soutar (1973), using Bradshaw's (1961), data concluded that small size in oxygen minima reflect optimal growth conditions. These environments provide sufficient oxygen for normal metabolic activity of smaller foraminifera, but may prohibit larger specimens from being successful.

Since small specimens require less oxygen and may take up oxygen more efficiently, it would be reasonable to expect them to predominate during an extensive and enduring anoxic episode. However, seasonal or episodic influxes of oxygenated water may permit larger foraminiferal specimens to inhabit basins. Once oxygen is depleted these large specimens die while smaller foraminifera survive (Bernhard, 1986).

The foraminiferal assemblages from the Down Cliff Clay (*levesquei* zone) at Eype show a return to a larger test size and greater diversity, indicative of more normal oxygenated conditions. The *Lenticulina muensteri* plexus group and *Marginulina* dominate these assemblages.

6.4.2 Correlation of Macrofaunal and Microfaunal Responses

Little's (1996) detailed biostratigraphic sampling of invertebrate macrofaunas through complete, expanded sequences in North Yorkshire, England and in southwest Germany shows that a species level event occurs in the early Toarcian. During the late Pliensbachian there was a diverse range of benthic species including infaunal and epifaunal bivalves, brachiopods and crinoids. The equally diverse nekton included ammonites and belemnites. While there was significant ecological disruption resulting from the onset of anoxia, the biotic responses of groups of organisms were markedly different. Taxa inhabiting the upper water column were unaffected by anoxia and included ammonites and belemnites. In addition, epifaunal taxa adapted to low-oxygen conditions such as the posidoniids and inoceramids, flourished in the post-extinction environment during the survival interval. As conditions ameliorated, the biota became more diverse and gradually began to resemble the pre-extinction biotas (Harries and Little, 1999).

This pattern was not reflected in the response of the micro-fauna and especially not in the case of benthic foraminifera. The post-extinction faunas were of a completely different character compared to the pre-extinction biotas and have greater affinities with Middle Jurassic foraminiferal faunas (e.g., Gordon, 1966; Norling, 1972; Tyszka, 1994).

Little (1995), using evidence from the North Yorkshire Coast and other northwest European sections, confirmed the Hallam (1986) model that the main species extinctions during the late Pliensbachian - early Toarcian time interval occurred, not at the end of the Pliensbachian (Sepkoski and Raup, 1986), but near the top of the early Toarcian *tenuicostatum* Zone. However, this event is only significant at species level; it cannot be recognised at genus level (Hallam, 1986) or at family level.

This study shows a species extinction event with a 19% (9 from 47 species) reduction in diversity at the top of the *tenuicostatum* Zone. This was followed by an 8% (3 from 38 species) reduction at during the *falciferum* Zone. The loss of foraminiferal species is low compared to the figures of Little (1996) who records a significant macro-species extinction event at the top of the *tenuicostatum* Zone with a 77% (17 from 22 species) reduction in diversity. The benthos was most severely affected, with an 88% species drop including the disappearance of the total infauna.

No major foraminiferal group suffered extinction over this interval but the important Lower Jurassic lageniids *Lingulina tenera*, *Frondicularia terquemi* and *Marginulina prima* plexi were eliminated; these seem to have been relatively shallow–water mid-shelf forms which were replaced by the very tolerant *Lenticulina*.

The generic diversity of the Lagenina continued to increase through the Mesozoic and showed no signs of decrease through the early Toarcian events (Tappan and Loeblich, 1988). Elevated, interconnected continents and restricted seaways in the Lower Jurassic resulted in the expansion of cosmopolitan smaller foraminifera. Common in the shales of the Jurassic (and Cretaceous), the flattened and elongate tests of the Lagenina were probably an adaption to burrowing in the upper few centimetres of organic-rich substrates, as detrital or bacterial scavengers. In contrast to these larger foraminifera of shallow water, the relatively small Nodosariidae, Vaginulinidae, as well as smaller Robertinina, thrived in the fine clastic sediments deposited in deeper waters. These foraminifera with flattened, lenticular, or low trochoid tests probably fed on bacteria or other protozoans, or were infaunal detrital feeders.

As a result, the Lagenina were not greatly affected by the environmental changes and resulting extinctions during the early Toarcian, but continued to show a slow and steady increase in diversity (Tappan and Loeblich, 1988).

As Little (1996) observes, although the macro-faunal species returning in the *bifrons* Zone are different from those of the lowest Toarcian, at the generic level over 90% are Lazarus taxa, recorded in sediments both below and above the Jet Rock *s.s.* Analysed at familial level there are no extinctions at all (Little and Benton, 1995).

The extinction event recorded in the early Toarcian sections is, therefore, only significant at species level. Bivalve mass extinction in the Andean Basin of South America was described by Aberhan and Fürsich (2000) as showing a sharp drop in species diversity, caused mainly by extinction of endemics and an extended lag phase. They also found that while analysis of community attributes such as guild diversity, number of associations and species richness of samples constituting association did not yield any significant changes across the critical interval, rates of originations and extinction of species differed markedly between the various substages of the Early Jurassic. In the model proposed by Aberhan and Fürsich (1997) the preferential disappearance of endemics was explained by the immigration of, and competitive replacement by, cosmopolitan species. While the spread of cosmopolitans at the expense of endemics would reduce diversity on a global scale, a regional effect would only become noticeable if a cosmopolitan species replaces two or more endemics. However, Aberhan and Fürsich (2000) suggest that rather than palaeoceanographic factors such as sea-level changes, productivity and climate and the resulting spread of anoxia being responsible for the marked reduction in diversity, the model must be modified to include an important evolutionary component, independent of environmental changes during the extinction interval. Alternatively, they propose that a burst in the origination rate of endemic bivalves in the Early Pliensbachian contributed considerably to their marked diversity decline several million years later, in the Late Pliensbachian.

Community replacement, involving gradual abrupt substitution of one benthic community for another as a result of subtle to sharp changes in habitats over sub-evolutionary time (Miller, 1986), could also explain the changes seen in the foraminiferal faunas during the Pliensbachian - Toarcian interval. The environments during this period changed quite rapidly, featuring a type of community replacement involving species turnover, where environmental tolerance limits of certain species of foraminifera were closely approached or exceeded. It is notable that the origination rate during this period was quite low, illustrated by zone in Table 12.

Ammonite Zone	m	sp	te	f	bi
Originations	3	1	0	0	0
Extinctions	1	1	9	3	1
No. of species	26	43	47	21	26
Turnover %	8	2	10	7	2

Table 12. Zonal distribution of originations, extinctions and foraminiferal species diversity for the late Pliensbachian and early Toarcian. Turnover is explained in the text. Data from Table 5. m - margaritatus; *sp -* spinatum; *te -* tenuicostatum; *f -* falciferum; *bi -* bifrons *Zones.*

Turnover rate is a measure determined by averaging the number of originations and extinctions and dividing by the total number of taxa and is expressed as a percentage (after Hallam, 1987). Copestake (1978) notes that 42 species from the Mochras Borehole have ranges from the Pliensbachian, through the *falciferum* Zone events and persist into the uppermost Toarcian.

The replacement of (possibly extinct) species in the foraminiferal faunas is borne out by the low rates of origination and the dominance of species like *Lenticulina muensteri* after the *falciferum* Zone events. The assemblages in the mid-Upper Toarcian are composed of species that, while contributing to earlier assemblages, now have a greater dominance and have presumably taken over the niches previously occupied members of the *Lingulina tenera* and *Marginulina prima* plexus groups and to a certain extent species of *Nodosaria.*

6.5 Summary

Palaeoecological interpretations of Jurassic foraminiferal assemblages are frequently problematic owing to the lack of direct Recent analogues. This is the result of drastic changes which took place in the nature of benthic shelf assemblages during the Cretaceous and Tertiary.

The determination of depth of sea remains a difficult challenge but a significant advance could be made by using foraminiferal data. The application of foraminifera data to interpretation of palaeobathymetry makes use of the predictable recurrence of particular benthic biofacies with depth zones.

Within nodosariid-dominated populations, major variations in specific and generic abundance are seen in taxa which are long-ranging, suggesting controlling palaeoenvironmental factors.

While Lower Jurassic assemblages are dominated by the Suborder Lagenina, certain combinations of the principal faunal components appear repeatedly. Within this limited fauna, certain associations, found repeatedly in the successions, are replaced by other combinations. In the change from one environment to another, one or more of the principal components are usually replaced by others. Therefore, different environments of deposition result in different combinations of principal components.

The distribution of foraminiferal biofacies, in comparison with other palaeoecological and sedimentological indicators, allow the construction of relative sea-level curves. These interpreted sea-level curves can then be compared with published sea-level curves and sequence stratigraphic interpretations.

6.6 Conclusions

While there is little facies evidence for a major sea-level drop around the end of the Hettangian at East Quantoxhead, interpretation of foraminiferal assemblages provides evidence for a minor regression. Following this regression at the end of the Hettangian a transgressive event coincides with the deposition of organic-rich mudstones associated with the periodic development of low-oxygen bottom waters. It is also notable, from other studies, that several index foraminifera become extinct at or near the top of the Hettangian *angulata* Zone. Foraminiferal data also gives some support for a transgression across the Sinemurian - Pliensbachian boundary of the Cleveland Basin.

The foraminiferal data would appear to lend support to sea level forcing of adaptive radiations and extinctions. Falling sea level, as with any environmental change causes a turnover in the foraminiferal assemblages. The continuous rise in sea-level during the Lower Jurassic can be linked to a general increase in diversity of foraminiferal species, up until the early Toarcian.

The microfaunal response to the events discussed correlates with the macrofaunal response to the extent that neither are recognisable at family-level but there is a five-zone phase of extinction from the late Pliensbachian into the early Toarcian.

The Lower Jurassic foraminiferal fossil record provides additional, useful data on the rates of change and ecological effects of the Toarcian extinction event. Given the wide ranges of such effects, for example, between successive ammonite families and whole invertebrate faunas, the only kind of biological competition that is plausible to invoke is *pre-emptive* rather than *displacive* (Hallam, 1987). Indeed, the foraminiferal data show no evidence of progressive displacement of older by younger faunas. Instead certain species only expanded their populations and diversity significantly after the extinction of similar niche-occupying species.

Chapter 7 Summary and Conclusions

7.1 Summary

This study was based on high resolution sampling and study of Lower Jurassic fossiliferous sections in north west Europe, ranging from south west Germany, through France and southern England to the north Yorkshire coast. The focus was on the foraminiferal faunas of the Hettangian-Sinemurian boundary, Sinemurian- Pliensbachian boundary sequences of the UK and the Upper Pliensbachian - Lower Toarcian successions of north-west Europe. Seventy one foraminiferal species have been recovered and identified during this study comprising 23 genera from 11 families and 6 suborders.

Sea-level rise across the Pliensbachian - Toarcian boundary culminated in the *falciferum* Zone of the Toarcian and is one of the best authenticated eustatic events in the Jurassic. This major transgressive pulse was marked by deep water marine sequences and was associated with the deposition of organic-rich shales.

The development of anoxia coincides with a notable period of mass extinction of the marine fauna. High resolution sampling and study of the microfaunas through several sequences in the United Kingdom confirm that benthic foraminiferal faunas were similarly affected by an early Toarcian *falciferum* Zone event. Samples were analysed from Pliensbachian - Toarcian mudstone, clay and shale sequences of the South Dorset Coast, the Midlands and the Yorkshire Coast. The sections studied show distinct changes in assemblages across the Pliensbachian - Toarcian boundary and in the basal zones of the Toarcian.

A fundamental turnover in the foraminiferal assemblage occurs in the *falciferum* Zone during which many foraminiferal taxa become extinct. While large scale benthic foraminiferal trends have been previously identified, this high resolution study has revealed the existence of opportunist, or disaster, foraminiferal species. These species occur during times of environmental stress and exploit available ecological space for short periods of time.

Evidence for a foraminiferal extinction event in the Pliensbachian - Toarcian includes the elimination of the important Lower Jurassic *Lingulina tenera, Frondicularia terquemi* and *Marginulina prima* plexus groups, initiating a significant period of turnover of the microfauna. A marked change also occurred in the character of associated nodosariid assemblages: the uniserial forms of *Nodosaria, Frondicularia* and *Lingulina*, dominating the Pliensbachian assemblages, were largely replaced by coiled *Lenticulina* in the early Toarcian. A reduction in test size and a decline in species diversity, compared with Hettangian to Sinemurian foraminiferal assemblages, reflect the development of low oxygen conditions followed by a subsequent renewal of the microfauna in the Middle Toarcian.

Interpretations of Early Jurassic palaeoenvironments based upon foraminiferal associations generally match sea-level change curves and agree with sedimentological evidence. The response of benthic foraminifera during the late Pliensbachian - early Toarcian can be linked to the changes in sea-level and the resulting development of low oxygen conditions. Uniserial forms such as *Nodosaria, Frondicularia* and *Lingulina* which dominate Pliensbachian assemblages become less important in Toarcian and subsequent assemblages, whereas the coiled forms like *Lenticulina* dominate after the event. Generalists (e.g., *Lenticulina*) probably had physiological characteristics that allowed them to survive low oxygen conditions and contribute to the rapid recovery that started in the *falciferum* Subzone.

A second approach taken in this study, aimed to extract as much palaeoenvironmental information as possible from the sample sets, characterised the microfacies in order to determine:

- the presence or absence of benthic microfauna in samples that could not be disagregated using available techniques was using thin-section examination,
- palaeoenvironmental data where foraminiferal evidence was lacking, especially critical during peak-anoxic conditions,
- the relationship between trace elements and the development of anoxic conditions and changes in sea-level.

The results of this study would seem to indicate that the laminations, rather than reflecting annual changes in sedimentation, actually represent fluctuations in rates of primary production (carbonate and organic matter) and clastic background sedimentation. The type, and degree, of lamination is directly controlled by the rate of deposition and physical form of the organic matter. The vertical progression from indistinct laminations, through the development of organic rich laminations and the return to indistinctly laminated mudstones is interpreted here to be a result of the changes in sedimentary processes from the initial dominance of bottom current action, to activity by benthic microbial mats, to suspension settling in deeper offshore water, modified by the occurrence of organic matter and the recovery from the low oxygen conditions.

The size distribution of pyrite framboids and lamination type has also been characterised in order to reconstruct the oxygenation histories together with evaluating environmental change. Within the well laminated organic rich microfacies (Jet Rock *s.s.* and lower Bituminous Shales) framboidal pyrite is dominant and ranges in size from 1-12μm. This narrow size range may reflect relatively short growth times, suggesting that most pyrite in these units formed near the sediment/water interface. Within the less restricted microfacies (Grey Shale and Alum Shale Member) pyrite framboids have a greater size distribution and other fabrics form, including large pyritic masses replacing shell fragments and burrow infills.

Trace Element Analysis was also performed on samples from the late Pliensbachian - early Toarcian of the north Yorkshire coast. Mn, in carbonate dominant sequences, has been considered to be a robust indicator of sea-level change, increases of Mn being associated with condensed sequences and maximum flooding surfaces. Although the significance of Mn within mudstone dominated sequences is less clear, Mn-rich carbonates are widely observed in early Toarcian anoxic carbon-rich deposits from Europe. Minimum Al values (indicative of reduced clay input) and maxima of Ca and Mn at the base of the *falciferum* Subzone may be an artifact of condensation of carbonate material possibly due to sediment starvation and correspond to published estimates of a maximum flooding surface. The increases in Ba are interpreted as short term pulses of increased fertility. The observed Ba peaks are not synchronous with Ca which may indicate that black shale deposition is productivity driven.

Global Stratotype Sections and Points (GSSPs)

This study has also contributed useful data towards the assessment of two Global Stratotype Sections and Points for two stages of the Lower Jurassic (Hylton, 1998; Hylton, 1999, Page *et al.*, 2000):

- The ranges of identified foraminiferal taxa at East Quantoxhead have been extended and provide further data to assist in the definition of the base of the Sinemurian stage.
- The foraminiferal faunas at Robin Hood's Bay have been investigated. The consistent appearance of *Dentalina matutina* is diagnostic of the Sinemurian - Pliensbachian boundary (Copestake and Johnson, 1989) while the first appearance of *Frondicularia terquemi muelensis* is seen at the base of the *raricostatum* Zone in the British Jurassic. The long-ranging, characteristic members of Lower Jurassic foraminiferal assemblages are also present at this locality: *Lingulina tenera tenera, Lingulina tenera tenuistriata, Lenticulina muensteri muensteri* and *Marginulina prima prima*

7.2 Conclusions

As a result of the studies undertaken during this research project a number of conclusions have been drawn:

1. The foraminiferal extinction event recorded in the early Toarcian sections of north west Europe is only significant at species level. No extinctions at the family-level occurred.
2. The foraminiferal data do not, therefore, support the hypothesis of periodicity in extinction of marine families and genera.
3. The foraminiferal data show no evidence of progressive displacement of older by younger faunas. Instead, certain species only expanded their populations and diversity significantly after the extinction of similar niche-occupying species.
4. The distribution of foraminiferal biofacies, in comparison with other palaeoecological and sedimentological indicators, allow the construction of relative sea-level curves. These interpreted sea-level curves compare well with published sea-level curves and sequence stratigraphic interpretations.

5. The Early Jurassic was characterised by a steadily rising relative sea-level punctuated by regressions and more rapid transgressions. Benthic foraminiferal faunas changed in response to the fluctuating sea-floor conditions and this study shows evidence of continual benthic community replacement and in some cases the proliferation of generalist species.

6. There is little evidence to suggest sea-level forcing of adaptive radiations or extinctions. Rather, there is a process of niche filling by other species and occasional abundant occurrences of otherwise background species.

7. The onset of low-oxygen conditions during the early Toarcian, culminating in the *exaratum* Subzone appears to be responsible for the extinctions seen around this event. The species that became extinct were not adapted to survive in the low-oxygen, 'soupy' conditions surrounding the peak anoxic events.

8. The foraminiferal response follows a similar pattern to the macrofauna. However, the repopulation faunas differ in that the foraminiferal assemblages feature many species that survived the *falciferum* Zone events.

9. The benthic foraminiferal species distribution, in parallel with the determination of a suite of trace elements and a systematic characterisation of the microfacies has permitted an assessment of the response and effect of sea-level change and oceanic anoxia and the usefulness of geochemistry in identifying environmental change in mudrock dominated sequences.

7.3 Scope for further work

Changes in foraminiferal assemblages are considered to be a response to sea-level changes where transgressions mark the arrival of new species and regressions, and times of lowered sea-level, appear to equate to extinctions. The interpreted palaeoenvironmental ranges of Lower Jurassic foraminiferal species remain broad, varying between the inner and outer shelf and further work to establish environmental parameters of these species is required.

Given the probability that many stratigraphic sections do not possess entire species ranges, the assumption that first and last appearances do record evolution and extinction events can seriously compromise stratigraphic conclusions (Mann & Lane, 1995). One technique of correlation does not make such *a priori* assumptions and commonly demonstrates that many sections contain ranges that are incomplete. This attribute makes the method of *Graphic Correlation,* initially proposed by Shaw (1964), one of the most powerful stratigraphic techniques available. The foraminiferal and geochemical data collected during this study could be used to independently determine the correct sequence of biostratigraphic events between the localities sampled.

During the preparation of samples several techniques were tried. Comprehensive treatment using the most effective technique was, however, prohibited owing to expense. Future studies could increase the recovery of microfaunas by the use of sodium tetraphenylborate (NaTBP) and sodium chloride, as described by Martin-Hanken (1979).

Unpublished data (Copestake and Johnson, 1989; Muller, 1990) indicate that the Hebrides Basin has an, as yet, unexplored potential for yielding foraminiferal faunas of Early Jurassic age. Skye, Raasay, Pabay and Morvern have extensive and unstudied exposures of shallow-marine to marginal marine mudstones and siltstones comprising the lower Lias Group (Hesselbo *et al.*, 1998). Other potential areas for comparative work include the coastal sections of Portugal (near Peniche) as well as inland exposures in northern Spain.

Plates 1 - 10

Plate 1

Ammodiscus, Haplophragmoides, Lagenammina, Opthalmidium

Spirillina, Thurammina, Trochammina.

Figures

1, 4, 5. *Ammodiscus siliceous* (Terquem), Scale bars 100µm. 1, 5. Main Alum Shales, south of Peak, Yorkshire, *fibulatum* Subzone. 4. Truc de Balduc, *hawskerense* Subzone.

2, 3. *Spirillina infima* (Strickland), Scale bars 100µm. 2. Main Alum Shales, south of Peak, Yorkshire, *fibulatum* Subzone. 3. Dotternhausen, *semicelatum* Subzone.

6, 9, 10, 19. *Trochammina canningensis* Tappan, Scale bars 50µm. Main Alum Shales, south of Peak, Yorkshire, *fibulatum* Subzone. 9. ventral view, showing small number of much inflated chambers.

7. *Thurammina jurensis* (Franke). Scale Bar 50µm. Dotternhausen, *paltum* Subzone

8. *Trochammina topagorukensis* Tappan. Scale bar 50µm. Yorkshire, Main Alum shales, *fibulatum* Subzone.

11-14. *Lagenammina jurassica* (Barnard), Scale bars 100µm. 11. Down Cliff Clay, Eype, *levesquei* Subzone. 12. Main Alum Shales, south of Peak, Yorkshire, *fibulatum* Subzone. 13, 14. Dotternhausen, *semicelatum* Subzone.

15. *Ammobaculites fontinensis* (Terquem). Scale bar 100µm. Eype, Downcliff Clay, *levesquei* Zone.

16. *Haplophragmoides kingakensis* Tappan, Scale bar 100μm. Main Alum Shales, south of Peak, Yorkshire, *fibulatum* Subzone.

17. *Haplophragmoides barrowensis* Tappan, Scale bar 100μm. Main Alum Shales, south of Peak, Yorkshire, *fibulatum* Subzone.

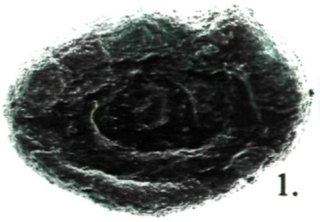
18. *Trochammina sablei* Tappan, Scale bar 100μm. Main Alum Shales, south of Peak, Yorkshire, *fibulatum* Subzone.

21, 22. *Trochammina occulta* (Bach); Scale bars 100μm. Main Alum Shales, south of Peak, Yorkshire, *fibulatum* Subzone.

23, 24. *Opthalmidium macfadyeni* Wood and Barnard, transmitted light. Dotternhausen, *paltum* Subzone. 23. Height 1.39mm, width 0.72mm. 24. Height 1.09mm, width 0.78mm.

25, 26. *Opthalmidum liascum* (Kübler and Zwingler), transmitted light. Dotternhausen, *paltum* Subzone. 25. Height 0.74mm, width 0.59mm. 26. Height 0.92mm, width 0.79mm.

Plate 1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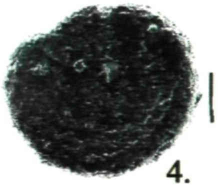
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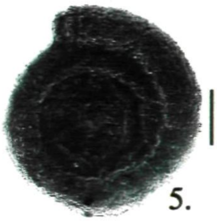
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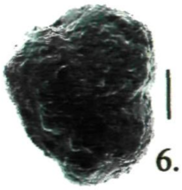
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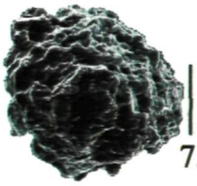
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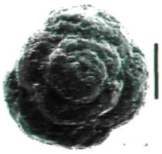
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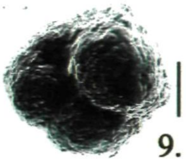
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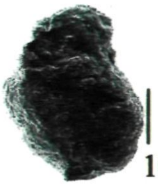
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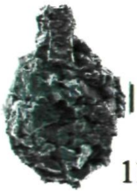
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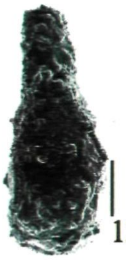
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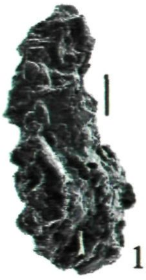
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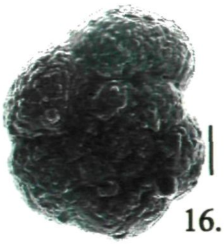
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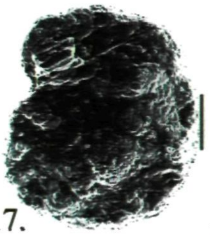
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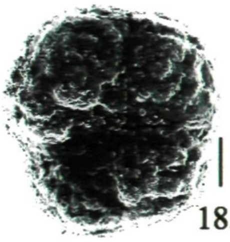
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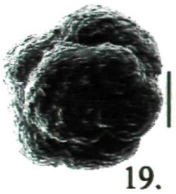
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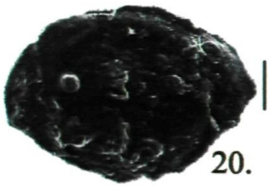
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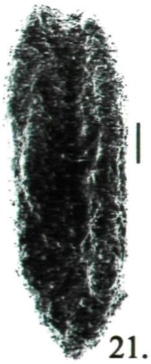
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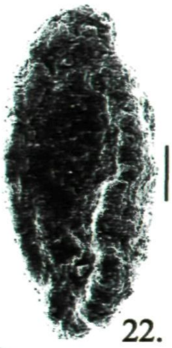
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Plate 2

Astacolus, Citharina

Figures 1, 9. *Astacolus pauperatus* (Jones and Parker), Scale bars 100μm. 1. Cement Shales, south of Peak, Yorkshire, *fibulatum* Subzone. 9. Main Alum Shales, south of Peak, Yorkshire, *fibulatum* Subzone.

2, 10, 11. *Astacolus primus* d'Orbigny, Scale bars 100μm. 2, 11. Blue Band, Eype, *margaritatus* Zone. 2. Adherent juvenile? 10. Form with initial keel.

Robin Hood's Bay, *aplanatum* Subzone.

3, 4, 6. *Astacolus / Vaginulinopsis speciosa* (Terquem), Scale bars 100μm.

3. Blue Band, Eype, *margaritatus* Zone. 4. Cement Shales, south of Peak, Yorkshire, *fibulatum* Subzone. 6. East Quantoxhead, *conybeari* Subzone.

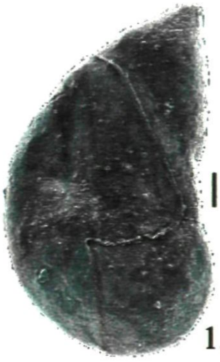
5. *Planularia protracta* (Bornemann), Scale bar 100μm. Blue Band, Eype, *margaritatus* Zone.

7. *Planularia inaequistriata* (Terquem), Scale bar 100μm. East Quantoxhead, *depressa* Subzone.

8. *Astacolus pediacus* Tappan, Scale bar 100μm. East Quantoxhead, *complanata* Subzone.

12. *Citharina colliezi* (Terquem), Scale bar 100μm. Down Cliff Clay, Eype, *levesquei* Subzone.

Plate 2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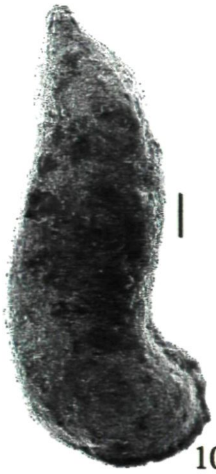
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Plate 3

Dentalina, Eoguttulina

Figures

1, 2. *Dentalina vetusta* d'Orbigny, Scale bars 100μm. 1. Truc de Balduc, *fibulatum* Zone. 2. Truc de Balduc *commune* Subzone.

3, 4. *Dentalina terquemi* d'Orbigny, Scale bars 100μm. 2. Dotternhausen, *semicelatum* Subzone. 3. Dotternhausen, *paltum* Subzone.

5, 6. *Dentalina pseudocommunis* Franke, Scale bars 100μm. 5. Dotternhausen, *clevelandicum* Subzone. 6. Main Alum Shales, south of Peak, Yorkshire, *fibulatum* Subzone.

7, 8. *Dentalina matutina* d'Orbigny, Scale bars 100μm. 7. East Quantoxhead, *conybeari* Subzone. 8. Siliceous Shales, Robin Hood's Bay, *aplanatum* Subzone.

9. *Dentalina vetustissima* d'Orbigny, Scale bar 100μm. Dotternhausen, *clevelandicum* Subzone.

10. *Dentalina tortilis* Franke, Scale bar 100μm. Tilton, *margaritatus* Zone.

11. *Dentalina varians* Terquem, Scale bar 100μm. Siliceous Shales, Robin Hood's Bay, *aplanatum* Subzone.

12. *Dentalina irregularis* Terquem, Scale bar 100 μm. Main Alum Shales, south of Peak, Yorkshire, *fibulatum* Subzone.

13, 14. *Eoguttulina liassica* (Strickland), Scale bars 50µm. 13. Dotternhausen, *paltum* Subzone. 14. East Quantoxhead, *complanata* Subzone.

15. *Eoguttulina simplex* (Terquem), Scale bar 100µm. Dotternhausen, *paltum* Subzone.

Plate 3

Plate 4

Frondicularia

Figures 1. *Frondicularia terquemi terquemi* d'Orbigny, Scale bar 100µm. Grey Shale Member, Brackenberry Wyke, *paltum* Subzone.

2, 6, 11, 13. *Frondicularia terquemi bicostata* d'Orbigny, Scale bars 100µm. 2. Siliceous Shales, Robin Hood's Bay, *aplanatum* Subzone. 6. Grey shale Member, Brackenberry Wyke, *paltum* Subzone. 11. Blue Band, Eype, *margaritatus* Zone. 13. Dotternhausen, *clevelandicum* Subzone.

3- 5, 7, 9. *Frondicularia terquemi sulcata* Bornemann. Scale bars 100µm. 3, 4. Barnard's form G. Siliceous Shales, Robin Hood's Bay, *aplanatum* Zone. 5. Barnard's form E. Blue Band, Eype, *margaritatus* Zone. 7. Barnard's form B, Siliceous Shales, Robin Hood's Bay, *aplanatum* Subzone. 9. Barnard's form F. Siliceous Shales, *aplanatum* Subzone.

8. *Frondicularia terquemi* Subsp. B. Copestake and Johnson, Scale bar 100µm. Blue Band, Eype, *margaritatus* Zone.

10, 12. *Frondicularia terquemi muelensis* Ruget and Sigal, Scale bars 100µm. 10. Truc de Balduc, *hawskerense* Subzone. 12. Dotternhausen, *clevelandicum* Subzone.

Plate 4

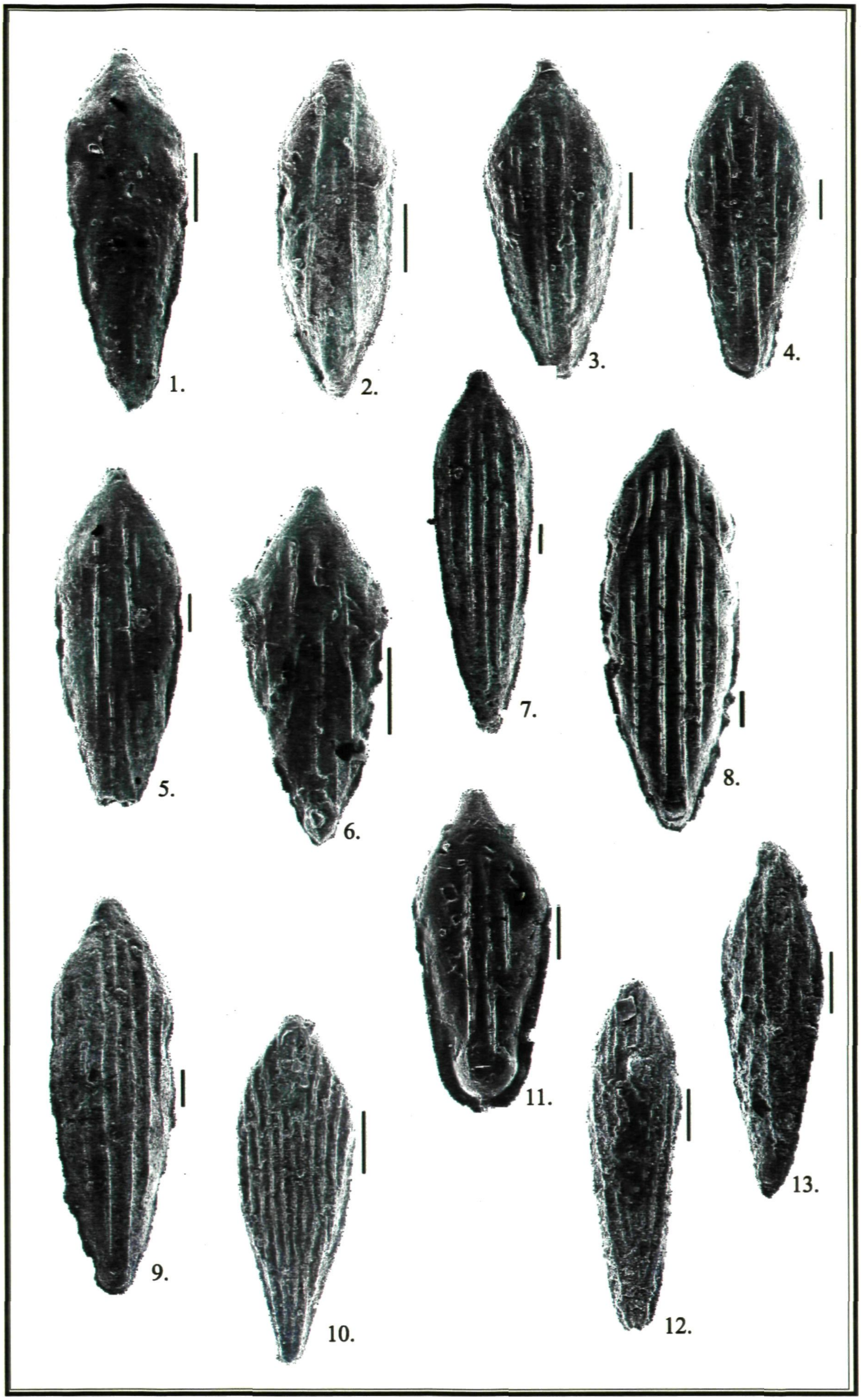

Plate 5

Lenticulina

Figures 1 *Lenticulina d'orbigny* Roemer.

Scale Bar 100µm. Eype, Downcliff Clay, *levesquei* Zone.

2, 3. *Lenticulina muensteri muensteri* (Roemer).

Scale bars 100µm. 2. Truc de Balduc, *spinatum* Zone. 3. Uncoiled form, Barnard's form G. Blue Band, Eype, *margaritatus* Zone.

4, 8, 10, 14. *Lenticulina varians* (Bornemann) plexus. Scale bars 100µm.

4. Dotternhausen, *semicelatum* subzone. 8. Truc de Balduc, *fibulatum* Subzone. 10. Uncoiled form, Barnard's form A. Eype, Downcliff Clay, *levesquei* Zone. 14. Dotternhausen, *commune* subzone, Scale bar 100 µm.

5, 15. *Lenticulina muensteri acutiangulata* (Terquem) 5. Dotternhausen, *semicelatum* Subzone, Scale bar 100µm. 15. Truc de Balduc, *hawskerense* Subzone, Scale bar 100µm.

6, 7. *Lenticulina foveolata* (Franke) Truc de Balduc, *fibulatum* Subzone, Scale bars 100µm.

9, 11, 13. *Lenticulina muensteri subalata* (Reuss). Truc de Balduc, *fibulatum* Subzone, Scale bars 100µm.

14. *Lenticulina muensteri polygonata* (Franke). Robin Hood's Bay, *aplanatum* Subzone, Scale Bar 100µm.

Plate 5


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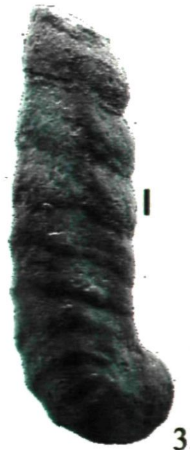
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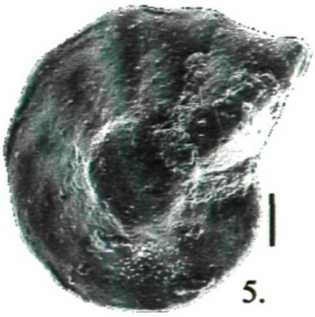
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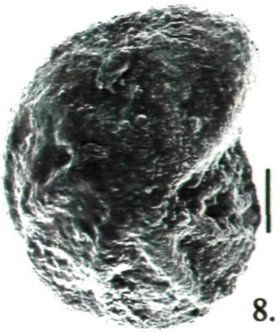
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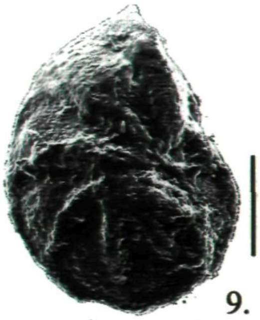
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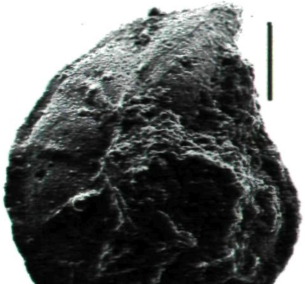
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Plate 6

Lingulina

Figures 1. *Lingulina tenera occidentalis* (Berthelin), Truc de Balduc, *hawskerense* Subzone, Scale bar 50µm.

2-4. *Lingulina tenera* Subsp. A Copestake and Johnson, Tilton, *margaritatus* Zone. Scale bars 50 µm.

6. *Lingulina tenera substriata* (Nørvang). East Quantoxhead, *bucklandi* Zone. Scale bar 100µm.

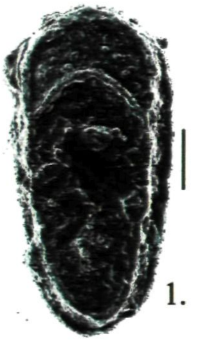
5, 10-12, 21. *Lingulina tenera tenera* (Bornemann), Scale bars 100µm. 5. Truc de Balduc, *hawskerense* Subzone. 10. Scale bar 50µm, Blue Band, Eype, *margaritatus* Zone. 11 Kettleness Member, Brackenberry Wyke, *gibbosus* Subzone. 12 Tilton, *margaritatus* Zone. 21 Truc de Balduc, *hawskerense* Subzone.

7-9, 15-17, 20. *Lingulina tenera pupa* (Terquem), Scale bars 100µm. 7 Truc de Balduc, *hawskerense* Subzone. 8, 15, 16, 17, 20. Blue Band, Eype, *margaritatus* Zone. 9. Apertural view of Fig 8, Scale bar 50µm.

13, 14, 19. *Lingulina tenera tenuistriata* (Nørvang). 13. Scale bar 50µm. Truc de Balduc, *hawskerense* Subzone. 14. Scale bar 100µm. Tilton, *margaritatus* Zone. 19. East Quantoxhead, *complanata* Subzone.

18. *Lingulina tenera collenoti* (Terquem), Scale bar 100µm. East Quantoxhead, *complanata* Subzone.

Plate 6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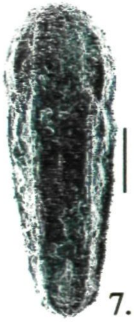
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Plate 7

Marginulina

Figures 1, 2. *Marginulina prima* plex. *insignis* (Franke), Scale bars 100µm. 1. Blue Band, Eype, *margaritatus* Zone. 2. Apertural view of same specimen.

3 - 8. *Marginulina prima* plex. *prima* d'Orbigny, 3. Dotternhausen, *clevelandicum* Subzone. 4. Apertural view of same specimen. 5, 6, 8. Grey Shales, Brackenberry Wyke, *paltum* Subzone. 7. Apertural view of fig. 6.

9 - 12. *Marginulina prima* plex. *praerugosa* Nørvang, Scale bars 100µm, Grey Shales, Brackenberry Wyke, *paltum* Subzone. 9. Apertural view of fig. 10, Scale bar 50µm.

13, 14. *Marginulina alata* Terquem, Scale bars 100µm. Dotternhausen, *clevelandicum* Subzone.

15 - 17. *Marginulina prima* plex. *rugosa*, Scale bars 100µm. 15. Grey Shales, Brackenberry Wyke, *paltum* Subzone. 16, 17. Dotternhausen, *clevelandicum* Subzone.

18. *Marginulina prima* plex. *interrupta* (Terquem), Scale bar 100µm. Dotternhausen, *clevelandicum* Subzone.

Plate 7


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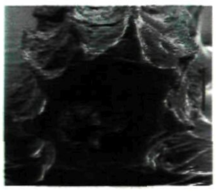
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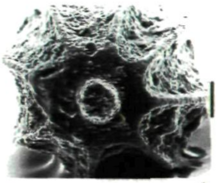
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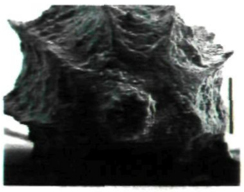
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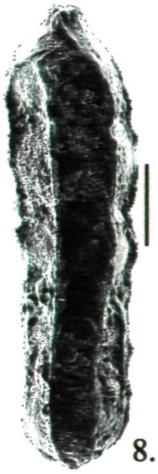
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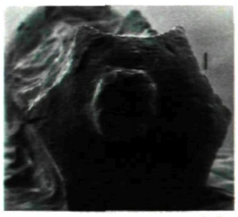
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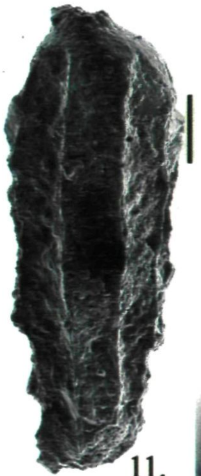
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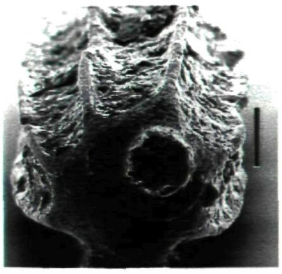
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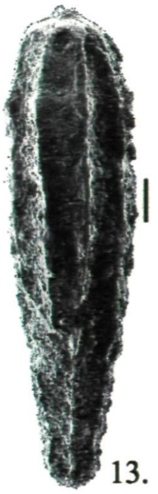
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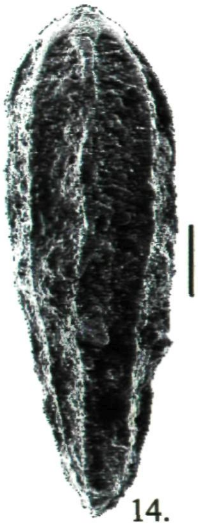
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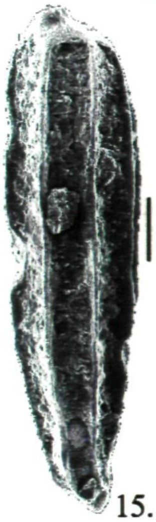
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Plate 8

Nodosaria, Pseudonodosaria, Lagena

Figures 1-2. *Nodosaria metensis* Terquem. 1. Scale bar 100µm. Blue Band, Eype, *margaritatus* Zone. 2. Apertural view of same specimen. Scale bar 50µm.

3, 4. *Nodosaria nitidana* Brand, Scale bars 100µm. Tilton, *falciferum* Subzone.

5. *Nodosaria simplex* (Terquem), Scale bar 100µm. East Quantoxhead, *complanata* Subzone.

6. *Nodosaria mitis* (Terquem and Berthelin), Scale bar 100µm. Down Cliff Clay, Eype, *levesquei* Subzone.

7. *Nodosaria fontinensis* Terquem, Scale bar 100µm. Tilton, *falciferum* Subzone.

8, 9. *Nodosaria dispar* Franke, Scale bars 100µm. Tilton, *falciferum* Subzone.

10. *Nodosaria kuhni* Franke, Scale bar 100µm. Tilton, *margaritatus* Zone.

11, 12, 13. *Pseudonodosaria vulgata* (Bornemann) gr., Scale bars 100µm. 11, 12. Tilton, *falciferum* Subzone. 13. Truc de Balduc, *hawskerense* Subzone.

14. *Lagena aphela* Tappan, Scale bar 100µm. Tilton, *margaritatus* Zone.

Plate 8


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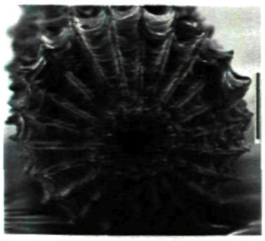
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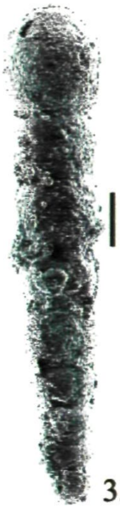
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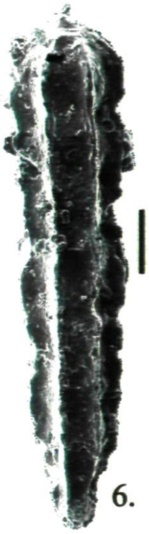
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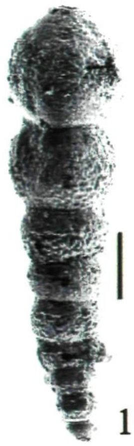
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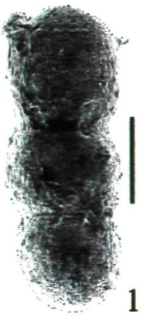
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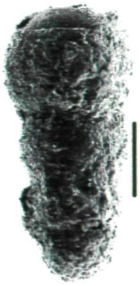

13.

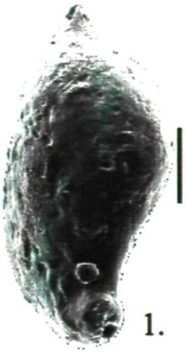

14.

Plate 9

Vaginulina, Brizalina, Reinholdella

Figure 1.	*Vaginulina listi* (Bornemann), Scale bar 100µm. Blue Band, Eype, *margaritatus* Zone.
2.	*Vaginulina simplex* (Terquem), Scale bar 100µm. Dotternhausen, *clevelandicum* Subzone.
3.	*Brizalina liassica* Terquem, Scale bar 100µm. Port Mulgrave, Yorkshire, *semicelatum* Subzone.
4, 5.	*Reinholdella pachyderma* Hofker, Scale bars 50µm. 4. Truc de Balduc, *commune* Subzone. 5. Side view of same specimen.
6, 7, 8.	*Reinholdella macfadyeni* (Ten Dam), Scale bar 100µm. 6, 7. Port Mulgrave, Yorkshire, *semicelatum* Subzone. 8. Brackenberry Wyke, Yorkshire *paltum* Subzone.
9, 10, 11.	*Reinholdella dreheri* (Bartenstein), Scale bars 100µm. 9, 10. Brackenberry Wyke, *paltum* Subzone. 11. Truc de Balduc, *fibulatum* Subzone.

Plate 9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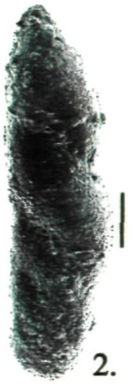
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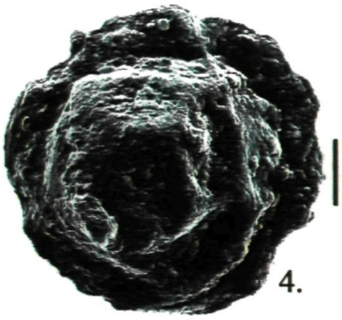
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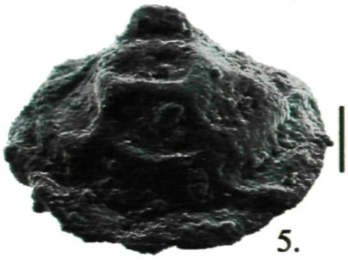
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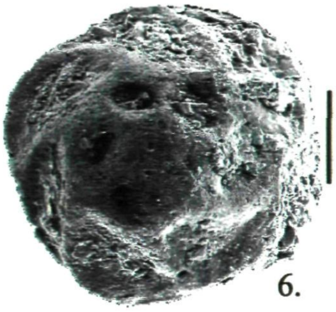
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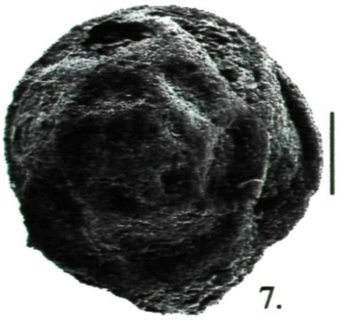
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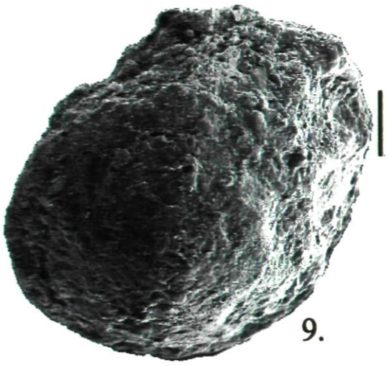
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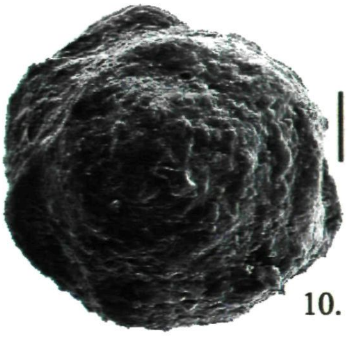
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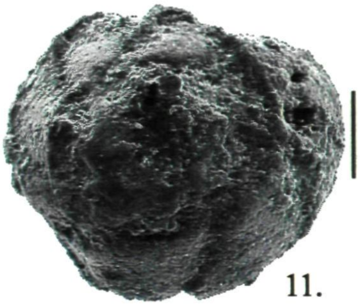
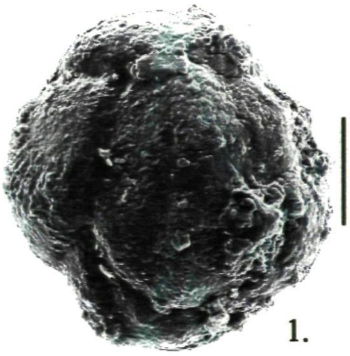

11.

Plate 10

Reinholdella

Figures 1-8. *Reinholdella? planiconvexa* (Fuchs), Scale bars 50μm. 1, 2. Tilton, *exaratum* Subzone. 3, 4. Tilton, *falciferum* Subzone. 5. Ventral view, Tilton, *falciferum* Subzone. 6. Eroded specimen showing internal chamber arrangement, Brown's Hill Quarry, *exaratum* subzone. 7. Brown's Hill Quarry, *exaratum* Subzone. 8. Brown's Hill Quarry, *falciferum* Subzone.

Plate 10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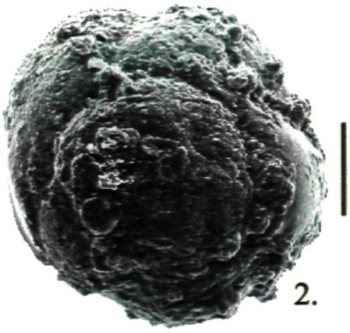
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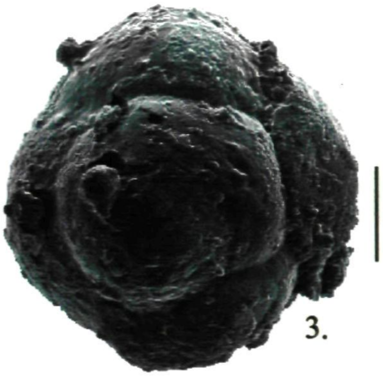
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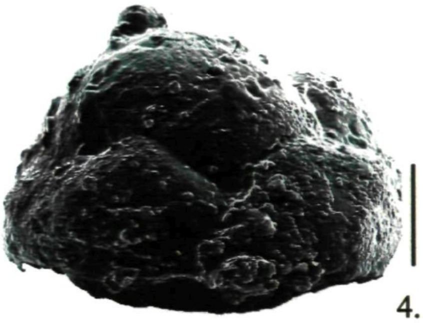
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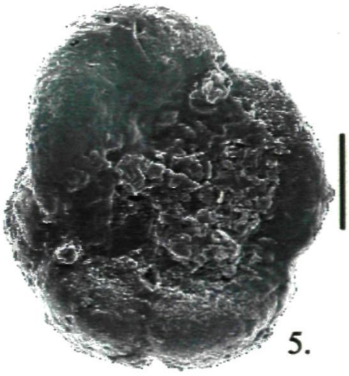
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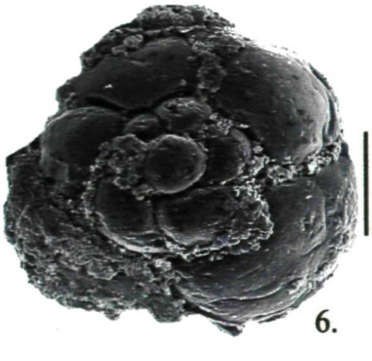
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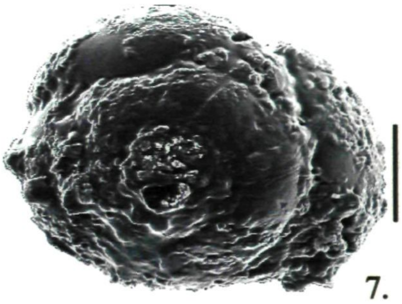
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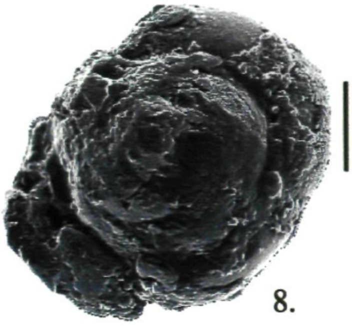
8.

Appendices

Appendix 1 - Sample processing log

Sample ID	Thin-Sec	Initial Proc	2ndary Proc	Fauna	Geochem		Sample ID	Thin-Sec	Initial Proc	2ndary Proc	Picked	Geochem
n=354												
Eype							**Truc de Balduc**					
DC1	No	Yes	No	23	No		TB1	Yes	Yes	No	301	No
DC2	No	Yes	No	Barren	No		TB2	No	Yes	No	303	No
DC3	No	Yes	No	Barren	No		TB3	Yes	Yes	No	302	No
DC4	No	Yes	Yes	4	No		TB4	No	Yes	No	293	No
DC5a	No	Yes	No	Barren	No		TB5	No	Yes	Yes	Barren	No
DC5b	No	Yes	No	Barren	No		TB6	No	Yes	Yes	301	No
DC6	No	Yes	No	1	No		TB7	Yes	Yes	Yes	Barren	No
DC7	No	Yes	No	Barren	No		TB8	No	Yes	Yes	Barren	No
DC8	No	Yes	No	51	No		TB9	Yes	Yes	Yes	Barren	No
DC9	No	Yes	No	34	No		TB10	No	Yes	Yes	Barren	No
DC10	No	Yes	No	29	No		TB11	Yes	Yes	Yes	Barren	No
THS1	No	Yes	No	Barren	No		TB12	No	Yes	Yes	Barren	No
THS2	No	Yes	No	Barren	No		TB13	Yes	Yes	Yes	Barren	No
BB1	No	Yes	No	311	No		TB14	No	Yes	Yes	Barren	No
BB2	No	Yes	No	Barren	No		TB15	Yes	Yes	Yes	Barren	No
DCS1	No	Yes	No	Barren	No		TB16	No	Yes	Yes	Barren	No
DCS2	No	Yes	No	Barren	No		TB17	Yes	Yes	Yes	Barren	No
DCS3	No	Yes	No	Barren	No		TB18	No	Yes	Yes	Barren	No
DCS4	No	Yes	No	Barren	No		TB19	No	Yes	Yes	Barren	No
DCS5	No	Yes	No	Barren	No		TB20	Yes	Yes	Yes	Barren	No
DCS6	No	Yes	No	15	No		TB21	No	Yes	Yes	Barren	No
DCS7	No	Yes	No	12	No		TB22	Yes	Yes	Yes	274	No
							TB23	No	Yes	Yes	Barren	No
Tilton							TB24	Yes	Yes	Yes	Barren	No
F1/1	No	Yes	Yes	Barren	No		TB25	No	Yes	Yes	Barren	No
F1/2	No	Yes	Yes	301	No		TB26	Yes	Yes	Yes	298	No
F1/3	No	Yes	Yes	Barren	No		TB27	Yes	Yes	Yes	Barren	No
F1/4	No	Yes	Yes	Barren	No		TB28	No	Yes	Yes	Barren	No
F1/5	No	Yes	Yes	Barren	No		TB29	No	Yes	Yes	221	No
F1/6	No	Yes	Yes	Barren	No		TB30	Yes	Yes	Yes	298	No
F1/7	No	Yes	Yes	Barren	No							
F1/8	No	Yes	Yes	Barren	No							
F1/9	No	Yes	Yes	149	No							
F1/10	No	Yes	Yes	301	No							
F1/11	No	Yes	Yes	301	No							
F1/12	No	Yes	Yes	301	No							
F2/1	Yes	**Marlstone**	Yes	Barren	No							
F2/2	Yes	**Rock**	Yes	Barren	No							
F2/3	Yes	**Bed**	Yes	Barren	No							
F3/1	No	Yes	Yes	301	No							
F3/2	No	Yes	Yes	Barren	No							
F3/3	No	Yes	Yes	Barren	No							
F3/4	No	Yes	Yes	Barren	No							
F3/2/1	No	Yes	Yes	310	No							
F3/2/2	No	Yes	Yes	Barren	No							
BH1/1	No	Yes	Yes	Barren	No							
BH1/2	No	Yes	Yes	Barren	No							
BH1/3	No	Yes	Yes	Barren	No							
BH1/4	No	Yes	Yes	Barren	No							
BH1/5	No	Yes	Yes	Barren	No							
BH2/1	No	Yes	Yes	Barren	No							

Sample ID	Thin-Sec	Initial Proc	2ndary Proc	Fauna	Geochem		Sample ID	Thin-Sec	Initial Proc	2ndary Proc	Fauna	Geochem
Dotternhausen Quarries							**North Yorkshire Coast**					
D1	No	Yes	Yes	Barren	No							
D2	No	Yes	Yes	Barren	No		PMG/B/1		Yes	Yes	Barren	Yes
D3	No	Yes	Yes	Barren	No		PMG/B/2		Yes	Yes	Barren	Yes
D4	No	Yes	Yes	Barren	No		PMG/B/3		Yes	Yes	Barren	Yes
D5	No	Yes	Yes	Barren	No		PMG/B/4		Yes	Yes	Barren	No
D6	No	Yes	Yes	Barren	No		PMG/B/5		Yes	Yes	Barren	No
D7	No	Yes	Yes	Barren	No							
D8	No	Yes	Yes	Barren	No		PMG/C/1		Yes	Yes	Barren	Yes
DT1	Yes	Yes	Yes	Barren	No		PMG/C/2		Yes	Yes	Barren	Yes
DT2	No	Yes	Yes	Barren	No		PMG/C/3		Yes	Yes	Barren	Yes
DT3	No	Yes	Yes	Barren	No		PMG/C/4		Yes	Yes	Barren	Yes
DT4	No	Yes	Yes	Barren	No		PMG/C/5		Yes	Yes	Barren	Yes
DT5	No	Yes	Yes	Barren	No		SN13/49		Yes	Yes	Barren	No
DT6	No	Yes	Yes	Barren	No		SN8/47		Yes	Yes	Barren	No
DT7	Yes	Yes	Yes	Barren	No		SN7/47		Yes	Yes	Barren	Yes
DT8	No	Yes	Yes	Barren	No		SN6/47		Yes	Yes	Barren	Yes
DT9	No	Yes	Yes	Barren	No		SN5/47		Yes	Yes	Barren	No
DT10	No	Yes	Yes	Barren	No		SN4/47		Yes	Yes	Barren	No
DT11	Yes	Yes	Yes	Barren	No		SN2/45		Yes	Yes	Barren	Yes
DT12	No	Yes	Yes	Barren	No		SN3/45		Yes	Yes	Barren	Yes
DT13	Yes	Yes	Yes	Barren	No		SN14/45		Yes	Yes	Barren	Yes
DT14	No	Yes	Yes	Barren	No		SN15/43		Yes	Yes	Barren	Yes
DT15	No	Yes	Yes	Barren	No		SN19/43		Yes	Yes	Barren	Yes
DT16	Yes	Yes	Yes	Barren	No		SN18/43		Yes	Yes	Barren	No
DT17	No	Yes	Yes	Barren	No		SN17/43		Yes	Yes	Barren	No
DT18	Yes	Yes	Yes	Barren	No		SN16/43		Yes	Yes	Barren	Yes
DT19	Yes	Yes	Yes	301	No		SN20/43		Yes	Yes	Barren	Yes
DT20	No	Yes	Yes	283	No		RB2/41		Yes	Yes	Barren	Yes
DT21	No	Yes	Yes	299	No		SE1/41		Yes	Yes	Barren	Yes
DT22	No	Yes	Yes	305	No		SE2/41		Yes	Yes	Barren	Yes
DT23	Yes	Yes	Yes	Barren	No		PM11/41		Yes	Yes	Barren	No
DT24	No	Yes	Yes	Barren	No		PM10/41		Yes	Yes	Barren	No
DT25	No	Yes	Yes	Barren	No		PM9/40		Yes	Yes	Barren	Yes
DT26	Yes	Yes	Yes	299	No		PM9/41		Yes	Yes	Barren	No
DT27	Yes	Yes	Yes	301	No		PM7/39		Yes	Yes	Barren	No
DT28	Yes	Yes	Yes	273	No		PM5/38		Yes	Yes	Barren	Yes
DT29	Yes	Yes	Yes	Barren	No		PM3/35		Yes	Yes	Barren	Yes
DT30	Yes	Yes	Yes	Barren	No		PM2/34		Yes	Yes	Barren	No
DT31	Yes	Yes	Yes	Barren	No		PM1/34		Yes	Yes	Barren	Yes
DT32	Yes	Yes	Yes	Barren	No		PM12/32		Yes	Yes	Barren	Yes
DT33	Yes	Yes	Yes	Barren	No		PM14/31		Yes	Yes	Barren	Yes
DT34	Yes	Yes	Yes	Barren	No		PM15/31		Yes	Yes	Barren	Yes
DT35	Yes	Yes	Yes	Barren	No		PM16/31		Yes	Yes	100	Yes
DT36	Yes	Yes	Yes	Barren	No		PM18/27		Yes	Yes	230	Yes
DT37	Yes	Yes	Yes	Barren	No							
DT38	Yes	Yes	Yes	Barren	No							
DT39	Yes	Yes	Yes	Barren	No							
DT40	No	Yes	Yes	Barren	No							
DT41	No	Yes	Yes	Barren	No							
DT42	Yes	Yes	Yes	Barren	No							
DT43	No	Yes	Yes	236	No							
DT44	Yes	Yes	Yes	Barren	No							
DT45	Yes	Yes	Yes	Barren	No							

Sample ID	Thin-Sec	Initial Proc	2ndary Proc	Fauna	Geochem
North Yorkshire Coast					
PMG/1/1	Yes	Yes	Yes	Barren	Yes
PMG/1/2	Yes	Yes	Yes	Barren	Yes
PMG/1/3	Yes	Yes	Yes	Barren	Yes
PMG/1/4	Yes	Yes	Yes	Barren	Yes
PMG/1/5	Yes	Yes	Yes	Barren	Yes
PMG/1/6	Yes	Yes	Yes	Barren	Yes
PMG/1/7	Yes	Yes	Yes	Barren	Yes
PMG/1/8	Yes	Yes	Yes	Barren	Yes
PMG/1/9	Yes	Yes	Yes	Barren	Yes
PMG/1/10	Yes	Yes	Yes	Barren	Yes
PMG/1/11	Yes	Yes	Yes	Barren	Yes
PMG/1/12	Yes	Yes	Yes	Barren	Yes
PMG/1/13	Yes	Yes	Yes	Barren	Yes
PMG/1/14	Yes	Yes	Yes	Barren	Yes
PMG/1/15	Yes	Yes	Yes	Barren	Yes
PMG/1/16	Yes	Yes	Yes	Barren	Yes
PMG/1/17	Yes	Yes	Yes	Barren	Yes
PMG/1/18	Yes	Yes	Yes	Barren	Yes
PMG/1/19	Yes	Yes	Yes	Barren	Yes
BRW/1/1	No	Yes	Yes	151	
BRW/1/2	Yes	Yes	Yes	Barren	Yes
BRW/1/3	Yes	Yes	Yes	Barren	Yes
BRW/1/4	No	Yes	Yes	Barren	
BRW/1/5	No	Yes	Yes	259	
BRW/1/6	No	Yes	Yes	Barren	Yes
BRW/1/7	No	Yes	Yes	Barren	Yes
BRW/1/8	No	Yes	Yes	279	Yes
BRW/1/9	No	Yes	Yes	318	Yes
BRW/1/10	No	Yes	Yes	306	
BRW/1/11	Yes	Yes	Yes	292	Yes
BRW/1/12	Yes	Yes	Yes	Barren	Yes
BRW/2/1	No	Yes	Yes	Barren	Yes
BRW/2/2	Yes	Yes	Yes	Barren	Yes
BRW/2/3	Yes	Yes	Yes	Barren	Yes
BRW/2/4	No	Yes	Yes	Barren	Yes
BRW/3/1	Yes	Yes	Yes	Barren	Yes
BRW/3/2	Yes	Yes	Yes	Barren	Yes
FOX/1/1	No	Yes	Yes	Barren	Yes
FOX/1/2	No	Yes	Yes	Barren	Yes
FOX/1/3	No	Yes	Yes	Barren	Yes
FOX/1/4	No	Yes	Yes	Barren	Yes
FOX/1/5	Yes	Yes	Yes	Barren	Yes
FOX/1/6	Yes	Yes	Yes	Barren	Yes
FOX/1/7	No	Yes	Yes	263	Yes
FOX/1/8	Yes	Yes	Yes	246	Yes
FOX/2/1	No	Yes	Yes	Barren	Yes
FOX/2/2	Yes	Yes	Yes	Barren	Yes
FOX/2/3	Yes	Yes	Yes	Barren	Yes
HFS/1/1	Yes	Yes	Yes	Barren	Yes
HFS/1/2	No	Yes	Yes	Barren	Yes
HFS/1/3	No	Yes	Yes	Barren	Yes
HFS/1/4	Yes	Yes	Yes	Barren	Yes
HFS/1/5	No	Yes	Yes	Barren	Yes
HFS/1/6	No	Yes	Yes	Barren	No
HFS/1/7	Yes	Yes	Yes	Barren	Yes
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PKS/1/4	Yes	Yes	Yes	Barren	Yes
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PKS/2/2	Yes	Yes	Yes	Barren	Yes
PKS/2/3	No	Yes	Yes	Barren	Yes
PKS/2/4	Yes	Yes	Yes	Barren	Yes
PKS/2/5	Yes	Yes	Yes	Barren	Yes
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HFS/B/2	No	Yes	Yes	Barren	Yes
HFS/B/3	No	Yes	Yes	Barren	Yes
HFS/B/4	No	Yes	Yes	Barren	Yes
HFS/B/5	No	Yes	Yes	Barren	Yes
HFS/B/6	No	Yes	Yes	Barren	Yes
HFS/B/7	No	Yes	Yes	Barren	Yes
HFS/C/1	No	Yes	Yes	Barren	Yes
HFS/C/2	No	Yes	Yes	157	Yes
HFS/C/3	No	Yes	Yes	255	Yes
HFS/C/4	No	Yes	Yes	280	Yes
HFS/C/5	No	Yes	Yes	Barren	Yes
HFS/C/6	No	Yes	Yes	Barren	Yes
HFS/C/7	No	Yes	Yes	185	Yes
HFS/C/8	No	Yes	Yes	Barren	Yes
HFS/C/9	No	Yes	Yes	Barren	Yes
HFS/C/10	No	Yes	Yes	Barren	Yes
HFS/D/1	No	Yes	Yes	Barren	Yes
HFS/D/2	No	Yes	Yes	Barren	Yes
HFS/D/3	No	Yes	Yes	Barren	Yes
HFS/D/4	No	Yes	Yes	Barren	Yes
HFS/D/5	No	Yes	Yes	Barren	Yes
HFS/D/6	No	Yes	Yes	Barren	Yes
HFS/D/7	No	Yes	Yes	Barren	Yes
HFS/D/8	No	Yes	Yes	Barren	Yes

Sample ID	Thin-Sec	Initial Proc	2ndary Proc	Fauna	Geochem		Sample ID	Thin-Sec	Initial Proc	2ndary Proc	Fauna	Geochem
Robin Hood's Bay							**East Quantoxhead**					
RBH/B/1	No	Yes	Yes	166	No		EQH1	No	Yes	Yes	Barren	No
RBH/B/2	No	Yes	Yes	Barren	No		EQH2	No	Limestone	No	Barren	No
RBH/B/3	No	Yes	Yes	Barren	No		EQH3	No	Yes	Yes	Barren	No
RBH/B/4	No	Yes	Yes	265	No		EQH4	No	Yes	Yes	182	No
RBH/B/5	No	Yes	Yes	Barren	No		EQH5	No	Limestone		Barren	No
RBH/B/6	No	Yes	Yes	Barren	No		EQH6	No	Yes	Yes	Barren	No
RBH/B/7	No	Yes	Yes	Barren	No		EQH7		Missing		Barren	No
RBH/B/8	No	Yes	Yes	Barren	No		EQH8	No	Yes	Yes	294	No
RBH/B/9	No	Yes	Yes	Barren	No		EQH9	No	Yes	Yes	Barren	No
RBH/B/10	No	Yes	Yes	Barren	No		EQH10	No	Yes	Yes	320	No
RBH/B/11	No	Yes	Yes	Barren	No		EQH11	No	Yes	Yes	Barren	No
RBH/B/12	No	Yes	Yes	Barren	No		EQH12	No	Yes	Yes	Barren	No
RBH/B/13	No	Yes	Yes	Barren	No		EQH13	No	Yes	Yes	302	No
RBH/B/14	No	Yes	Yes	Barren	No		EQH14	No	Yes	Yes	Barren	No
RBH/B/15	No	Yes	Yes	Barren	No		EQH15	No	Yes	Yes	Barren	No
RBH/B/16	No	Yes	Yes	Barren	No		EQH16	No	Yes	Yes	Barren	No
RBH/B/17	No	Yes	Yes	Barren	No		EQH17	No	Yes	Yes	Barren	No
RBH/B/18	No	Yes	Yes	182	No		EQH18	No	Yes	Yes	Barren	No
RBH/B/19	No	Yes	Yes	Barren	No		EQH19	No	Yes	Yes	Barren	No
RBH/B/20	No	Yes	Yes	Barren	No		EQH20	No	Yes	Yes	Barren	No
RBH/B/21	No	Yes	Yes	Barren	No		EQH21	No	Yes	Yes	Barren	No
RBH/B/22	No	Yes	Yes	Barren	No		EQH22	No	Yes	Yes	Barren	No
RBH/1/1	No	Yes	Yes	Barren	No		EQH23	No	Yes	Yes	Barren	No
RBH/1/2	No	Yes	Yes	Barren	No		EQH24	No	Yes	Yes	366	No
RBH/1/3	No	Yes	Yes	153	No		EQH25	No	Yes	Yes	Barren	No
RBH/1/4	No	Yes	Yes	Barren	No		QTX1	No	Yes	Yes	Barren	No
RBH/1/5	No	Yes	Yes	Barren	No		QTX2	No	Yes	Yes	Barren	No
RBH/1/6	No	Yes	Yes	Barren	No		QTX3	No	Yes	Yes	Barren	No
RBH/1/7	No	Yes	Yes	Barren	No		QTX4	No	Yes	Yes	Barren	No
RBH/1/8	No	Yes	Yes	Barren	No		QTX5	No	Yes	Yes	Barren	No
RBH/1/9	No	Yes	Yes	Barren	No		QTX6	No	Yes	Yes	24	No
RBH/1/10	No	Yes	Yes	Barren	No		QTX7	No	Yes	Yes	Barren	No
RBH/1/11	No	Yes	Yes	Barren	No		QTX8	No	Yes	Yes	Barren	No
RBH/1/12	No	Yes	Yes	Barren	No		QTX9	No	Yes	Yes	219	No
RBH/1/13	No	Yes	Yes	Barren	No		QTX10	No	Yes	Yes	340	No
RBH/2/1	No	Yes	Yes	Barren	No		QTX2/1	No	Yes	Yes	Barren	No
RBH/2/2	No	Yes	Yes	Barren	No		QTX2/2	No	Yes	Yes	295	No
RBH/2/3	No	Yes	Yes	Barren	No		QTX2/3	No	Yes	Yes	Barren	No
RBH/2/4	No	Yes	Yes	Barren	No		QTX2/4	No	Yes	Yes	301	No
RBH/2/5	No	Yes	Yes	Barren	No		QTX2/5	No	Yes	Yes	Barren	No
RBH/2/6	No	Yes	Yes	Barren	No		QTX2/6	No	Yes	Yes	Barren	No
RBH/2/7	No	Yes	Yes	Barren	No		QTX2/7	No	Yes	Yes	Barren	No
RBH/3/1	No	Yes	Yes	Barren	No		QTX2/8	No	Yes	Yes	Barren	No
RBH/3/2	No	Yes	Yes	Barren	No		QTX2/9	No	Yes	Yes	Barren	No
RBH/3/3	No	Yes	Yes	Barren	No		QTX2/10	No	Yes	Yes	Barren	No
							QTX2/11	No	Yes	Yes	299	No
							QTX2/12	No	Yes	Yes	Barren	No
							QTX2/13	No	Yes	Yes	Barren	No
							QTX2/14	No	Yes	Yes	Barren	No
							QTX2/15	No	Yes	Yes	Barren	No

Appendix 2 - Foraminiferal Data

Species / Samples	DCS7	DCS6	DC1	DC9	DC10	DC8
Lagenammina jurassica	2		2			5
Lagena aphela				1		
Ammodiscus siliceous						
Ammobaculites fontinensis						4
Haplophragmoides barrowensis						
Haplophragmoides kingakensis						
Thurammina jurensis						
Trochammina canningensis						
Trochammina occulta						
Trochammina sablei						
Trochammina topagorukensis						
Opthalmidium liascum						
Opthalmidium macfadyeni						
Nodosaria dispar		5				
Nodosaria fontinensis						
Nodosaria kuhni						
Nodosaria mitis				1		1
Nodosaria metensis						
Nodosaria nitidana						
Nodosaria simplex						
Citharina colleizi				2		
Dentalina matutina	1					
Dentalina irregularis						
Dentalina pseudocommunis						1
Dentalina terquemi						
Dentalina tortilis						
Dentalina varians						1
Dentalina vetustissima						1
Dentalina vetusta		1				
Astacolus pauperatus		3				
Astacolus pediacus						
Astacolus primus			2			
Astacolus / Vaginulinopsis speciosa						
Planularia inaequistriata						
Planularia protracta		1			1	
Frondicularia terquemi bicostata	3	2				
Frondicularia terquemi muelensis						
Frondicularia terquemi sulcata						
Frondicularia terquemi subsp. B						
Frondicularia terquemi terquemi						
Lenticulina d'Orbigny					5	2
Lenticulina foveolata						
Lenticulina muensteri muensteri	6		5	5	7	16
Lenticulina muensteri acutiangulata				10	8	13
Lenticulina muensteri polygonata				4		
Lenticulina muensteri subalata			14	6	4	3
Lenticulina varians				5	4	4
Marginulina alata						
Marginulina prima insignis						
Marginulina prima interrupta						
Marginulina prima praerugosa						
Marginulina prima prima		2				
Marginulina prima rugosa						
Pseudonodosaria vulgata						
Vaginulina listi						
Vaginulina simplex						
Lingulina tenera collenoti						
Lingulina tenera occidentalis						
Lingulina tenera subsp. A						
Lingulina tenera pupa						
Lingulina tenera substriata						
Lingulina tenera tenera		1				
Lingulina tenera tenuistriata						
Eoguttulina liassica						
Eoguttulina simplex						
Spirillina infima						
Brizalina liassica						
Reinholdella dreheri						
Reinholdella macfadyeni						
Reinholdella pachyderma						
Reinholdella? planiconvexa						
Sample Totals	**12**	**15**	**23**	**34**	**29**	**51**

Species / Samples	DC6	DC4	BB1	PM/18/27	PM/16/31	BRW/1/9
Lagenammina jurassica				4	7	
Lagena aphela						
Ammodiscus siliceous						
Ammobaculites fontinensis						
Haplophragmoides barrowensis						
Haplophragmoides kingakensis						
Thurammina jurensis						
Trochammina canningensis						
Trochammina occulta						
Trochammina sablei						
Trochammina topagorukensis						
Opthalmidium liascum						
Opthalmidium macfadyeni						
Nodosaria dispar						
Nodosaria fontinensis						
Nodosaria kuhni						
Nodosaria mitis						
Nodosaria metensis			3			
Nodosaria nitidana						
Nodosaria simplex						
Citharina colleizi						
Dentalina matutina						
Dentalina irregularis						
Dentalina pseudocommunis			6	2	1	
Dentalina terquemi			1	2		
Dentalina tortilis						
Dentalina varians						
Dentalina vetustissima						
Dentalina vetusta						
Astacolus pauperatus				3		
Astacolus pediacus						
Astacolus primus			5	3	6	
Astacolus / Vaginulinopsis speciosa			8			
Planularia inaequistriata						
Planularia protracta			4			
Frondicularia terquemi bicostata			3			
Frondicularia terquemi muelensis			1			
Frondicularia terquemi sulcata			2			
Frondicularia terquemi subsp. B			2			
Frondicularia terquemi terquemi						
Lenticulina d'Orbigny	1	4				
Lenticulina foveolata						
Lenticulina muensteri muensteri			32		1	1
Lenticulina muensteri acutiangulata			15			
Lenticulina muensteri polygonata						
Lenticulina muensteri subalata						
Lenticulina varians			9	4	6	2
Marginulina alata						
Marginulina prima insignis			3			
Marginulina prima interrupta						
Marginulina prima praerugosa						
Marginulina prima prima			21	18	4	5
Marginulina prima rugosa						
Pseudonodosaria vulgata						
Vaginulina listi			4			
Vaginulina simplex						
Lingulina tenera collenoti						
Lingulina tenera occidentalis						
Lingulina tenera subsp. A						
Lingulina tenera pupa			186			
Lingulina tenera substriata						
Lingulina tenera tenera			6			
Lingulina tenera tenuistriata						
Eoguttulina liassica						
Eoguttulina simplex						2
Spirillina infima						
Brizalina liassica				134	59	2
Reinholdella dreheri						2
Reinholdella macfadyeni				60	16	233
Reinholdella pachyderma						71
Reinholdella? planiconvexa						
Sample Totals	**1**	**4**	**311**	**230**	**100**	**318**

Species / Samples	**BRW/1/5**	**BRW/1/8**	**BRW/1/10**	**BRW/1/1**	**BRW/1/11**	**FOX/1/7**
Lagenammina jurassica	17	4	11			6
Lagena aphela						
Ammodiscus siliceous	1			1	1	16
Ammobaculites fontinensis					6	
Haplophragmoides barrowensis						34
Haplophragmoides kingakensis	1					
Thurammina jurensis				15		
Trochammina canningensis						11
Trochammina occulta		1				17
Trochammina sablei						43
Trochammina topagorukensis						
Opthalmidium liascum						
Opthalmidium macfadyeni						
Nodosaria dispar						
Nodosaria fontinensis						
Nodosaria kuhni						
Nodosaria mitis						
Nodosaria metensis						
Nodosaria nitidana						3
Nodosaria simplex						
Citharina colleizi						
Dentalina matutina						
Dentalina irregularis						
Dentalina pseudocommunis	11		1		2	
Dentalina terquemi	8	4			4	
Dentalina tortilis					4	
Dentalina varians	5		1			
Dentalina vetustissima						
Dentalina vetusta	5					
Astacolus pauperatus	3					2
Astacolus pediacus						
Astacolus primus	27	5		5	13	
Astacolus / Vaginulinopsis speciosa						
Planularia inaequistriata						
Planularia protracta						
Frondicularia terquemi bicostata						
Frondicularia terquemi muelensis	4	1				
Frondicularia terquemi sulcata	4					
Frondicularia terquemi subsp. B						
Frondicularia terquemi terquemi	5	1	2			
Lenticulina d'Orbigny						
Lenticulina foveolata						
Lenticulina muensteri muensteri	3					36
Lenticulina muensteri acutiangulata						
Lenticulina muensteri polygonata						
Lenticulina muensteri subalata						
Lenticulina varians	10	10	6	8	13	23
Marginulina alata						
Marginulina prima insignis						
Marginulina prima interrupta						
Marginulina prima praerugosa						
Marginulina prima prima	154	102	10	7	9	
Marginulina prima rugosa						
Pseudonodosaria vulgata						
Vaginulina listi						
Vaginulina simplex						
Lingulina tenera collenoti						
Lingulina tenera occidentalis						
Lingulina tenera subsp. A						
Lingulina tenera pupa				46		
Lingulina tenera substriata						
Lingulina tenera tenera				65	6	
Lingulina tenera tenuistriata						
Eoguttulina liassica						
Eoguttulina simplex	1					
Spirillina infima						
Brizalina liassica		151	87		127	
Reinholdella dreheri						
Reinholdella macfadyeni			35	4	30	20
Reinholdella pachyderma			153		77	52
Reinholdella? planiconvexa						
Sample Totals	**259**	**279**	**306**	**151**	**292**	**263**

Species / Samples	FOX/1/8	HFS/C/2	HFS/C/3	HFS/C/4	HFS/C/7	F1/02
Lagenammina jurassica			10	4	11	
Lagena aphela						12
Ammodiscus siliceous	14	46	120	53	5	
Ammobaculites fontinensis						
Haplophragmoides barrowensis	12					
Haplophragmoides kingakensis						
Thurammina jurensis						
Trochammina canningensis						
Trochammina occulta	13	12	5	8	31	
Trochammina sablei	8	15	22	48		
Trochammina topagorukensis						
Opthalmidium liascum						
Opthalmidium macfadyeni						
Nodosaria dispar						
Nodosaria fontinensis						
Nodosaria kuhni						
Nodosaria mitis						
Nodosaria metensis						
Nodosaria nitidana	11	15	32	21	10	3
Nodosaria simplex						
Citharina colleizi						
Dentalina matutina						
Dentalina irregularis						
Dentalina pseudocommunis			16	15		
Dentalina terquemi						
Dentalina tortilis						
Dentalina varians						
Dentalina vetustissima						
Dentalina vetusta						
Astacolus pauperatus	21			4	23	
Astacolus pediacus						
Astacolus primus		10	21	12	14	
Astacolus / Vaginulinopsis speciosa						
Planularia inaequistriata						
Planularia protracta						
Frondicularia terquemi bicostata						
Frondicularia terquemi muelensis						
Frondicularia terquemi sulcata						
Frondicularia terquemi subsp. B						
Frondicularia terquemi terquemi						
Lenticulina d'Orbigny						
Lenticulina foveolata						
Lenticulina muensteri muensteri	124				55	
Lenticulina muensteri acutiangulata						
Lenticulina muensteri polygonata						
Lenticulina muensteri subalata						
Lenticulina varians	43	12		5		
Marginulina alata						
Marginulina prima insignis						
Marginulina prima interrupta						
Marginulina prima praerugosa						
Marginulina prima prima						
Marginulina prima rugosa						
Pseudonodosaria vulgata						
Vaginulina listi						
Vaginulina simplex						
Lingulina tenera collenoti						
Lingulina tenera occidentalis						
Lingulina tenera subsp. A						
Lingulina tenera pupa						
Lingulina tenera substriata						
Lingulina tenera tenera						
Lingulina tenera tenuistriata						
Eoguttulina liassica						
Eoguttulina simplex						
Spirillina infima			14	4		13
Brizalina liassica						
Reinholdella dreheri						
Reinholdella macfadyeni			15	90	36	
Reinholdella pachyderma		47		16		
Reinholdella? planiconvexa						273
Sample Totals	**246**	**157**	**255**	**280**	**185**	**301**

Species / Samples	F3/1	F3/2/01	F1/09	F1/10	F1/11	F1/12
Lagenammina jurassica						
Lagena aphela				1		5
Ammodiscus siliceous						
Ammobaculites fontinensis						
Haplophragmoides barrowensis						
Haplophragmoides kingakensis						
Thurammina jurensis						
Trochammina canningensis						
Trochammina occulta						
Trochammina sablei						
Trochammina topagorukensis						
Opthalmidium liascum						
Opthalmidium macfadyeni						
Nodosaria dispar					4	
Nodosaria fontinensis				2	1	2
Nodosaria kuhni						
Nodosaria mitis						
Nodosaria metensis	11	13				
Nodosaria nitidana				5		1
Nodosaria simplex				1	2	
Citharina colleizi					1	
Dentalina matutina	6					
Dentalina irregularis						
Dentalina pseudocommunis						
Dentalina terquemi						
Dentalina tortilis		8				
Dentalina varians	8					
Dentalina vetustissima						
Dentalina vetusta						
Astacolus pauperatus	7				3	
Astacolus pediacus						
Astacolus primus	28	23	1			
Astacolus / Vaginulinopsis speciosa						
Planularia inaequistriata						
Planularia protracta						
Frondicularia terquemi bicostata						
Frondicularia terquemi muelensis						
Frondicularia terquemi sulcata						
Frondicularia terquemi subsp. B						
Frondicularia terquemi terquemi	12	4				
Lenticulina d'Orbigny						
Lenticulina foveolata						
Lenticulina muensteri muensteri	63	56				
Lenticulina muensteri acutiangulata						
Lenticulina muensteri polygonata						
Lenticulina muensteri subalata						
Lenticulina varians	48	41		2		1
Marginulina alata						
Marginulina prima insignis						
Marginulina prima interrupta						
Marginulina prima praerugosa						
Marginulina prima prima	3	21				
Marginulina prima rugosa						
Pseudonodosaria vulgata				2	6	11
Vaginulina listi						
Vaginulina simplex						
Lingulina tenera collenoti						
Lingulina tenera occidentalis						
Lingulina tenera subsp. A	82	121				
Lingulina tenera pupa		1				
Lingulina tenera substriata						
Lingulina tenera tenera	33	22				
Lingulina tenera tenuistriata						
Eoguttulina liassica						
Eoguttulina simplex					1	
Spirillina infima				4		3
Brizalina liassica						
Reinholdella dreheri						
Reinholdella macfadyeni						
Reinholdella pachyderma						
Reinholdella? planiconvexa			148	284	283	278
Sample Totals	**301**	**310**	**149**	**301**	**301**	**301**

Species / Samples	DT 19	DT 20	DT 21	DT 26	DT 22	DT 27
Lagenammina jurassica	7	2		6	4	5
Lagena aphela						
Ammodiscus siliceous	6	1	8	2	1	1
Ammobaculites fontinensis						
Haplophragmoides barrowensis						
Haplophragmoides kingakensis				8		3
Thurammina jurensis	13					
Trochammina canningensis						
Trochammina occulta				5		
Trochammina sablei						
Trochammina topagorukensis	10			12		
Opthalmidium liascum	3					
Opthalmidium macfadyeni	3					
Nodosaria dispar						
Nodosaria fontinensis		2				
Nodosaria kuhni						
Nodosaria mitis						
Nodosaria metensis			9	14		2
Nodosaria nitidana						
Nodosaria simplex	14		18	8		
Citharina colleizi						
Dentalina matutina						
Dentalina irregularis						
Dentalina pseudocommunis	13	8			5	3
Dentalina terquemi	9	10	17	12		
Dentalina tortilis						
Dentalina varians	8	2		15	6	
Dentalina vetustissima		4			3	
Dentalina vetusta			12	16		
Astacolus pauperatus						
Astacolus pediacus						
Astacolus primus						
Astacolus / Vaginulinopsis speciosa						
Planularia inaequistriata						
Planularia protracta						
Frondicularia terquemi bicostata					1	
Frondicularia terquemi muelensis						
Frondicularia terquemi sulcata						
Frondicularia terquemi subsp. B						
Frondicularia terquemi terquemi						
Lenticulina d'Orbigny						
Lenticulina foveolata						
Lenticulina muensteri muensteri	41	117	29		138	
Lenticulina muensteri acutiangulata		2	10	54		100
Lenticulina muensteri polygonata				10		11
Lenticulina muensteri subalata		3				
Lenticulina varians	20	1	13	8		58
Marginulina alata	6			14	4	
Marginulina prima insignis	7					
Marginulina prima interrupta					2	
Marginulina prima praerugosa						
Marginulina prima prima	44	37	28	55	40	67
Marginulina prima rugosa						
Pseudonodosaria vulgata	12		24			
Vaginulina listi						
Vaginulina simplex					3	
Lingulina tenera collenoti						
Lingulina tenera occidentalis						
Lingulina tenera subsp. A						
Lingulina tenera pupa						
Lingulina tenera substriata						
Lingulina tenera tenera	85	90	65	10	76	
Lingulina tenera tenuistriata						
Eoguttulina liassica			28	20	4	13
Eoguttulina simplex		4			14	12
Spirillina infima						
Brizalina liassica						
Reinholdella dreheri						
Reinholdella macfadyeni						
Reinholdella pachyderma			38	30		26
Reinholdella? planiconvexa					4	
Sample Totals	**301**	**283**	**299**	**299**	**305**	**301**

Species / Samples	DT 28	DT 43	TB 1	TB 2	TB 3	TB 4
Lagenammina jurassica	10			2	5	
Lagena aphela			12	4	5	12
Ammodiscus siliceous			4	6	8	
Ammobaculites fontinensis						
Haplophragmoides barrowensis						
Haplophragmoides kingakensis	16					
Thurammina jurensis						
Trochammina canningensis						
Trochammina occulta						
Trochammina sablei						
Trochammina topagorukensis		11				
Opthalmidium liascum					2	48
Opthalmidium macfadyeni					3	43
Nodosaria dispar				1		
Nodosaria fontinensis		8			2	
Nodosaria kuhni						
Nodosaria mitis			1			
Nodosaria metensis				1		
Nodosaria nitidana					2	
Nodosaria simplex			1	1		
Citharina colleizi						
Dentalina matutina						
Dentalina irregularis					4	
Dentalina pseudocommunis	1			7	6	
Dentalina terquemi			12			
Dentalina tortilis						
Dentalina varians	1		5	4	4	
Dentalina vetustissima			1		1	5
Dentalina vetusta				2	6	7
Astacolus pauperatus						7
Astacolus pediacus						
Astacolus primus		50				
Astacolus / Vaginulinopsis speciosa			1			
Planularia inaequistriata						
Planularia protracta						
Frondicularia terquemi bicostata						
Frondicularia terquemi muelensis				1		
Frondicularia terquemi sulcata						
Frondicularia terquemi subsp. B						
Frondicularia terquemi terquemi					1	4
Lenticulina d'Orbigny						
Lenticulina foveolata		28		2		3
Lenticulina muensteri muensteri		76	17	68	80	51
Lenticulina muensteri acutiangulata	130					
Lenticulina muensteri polygonata	70					
Lenticulina muensteri subalata						
Lenticulina varians	24		13	13	46	
Marginulina alata						
Marginulina prima insignis					15	7
Marginulina prima interrupta						
Marginulina prima praerugosa						
Marginulina prima prima	17		23	15	21	23
Marginulina prima rugosa					3	
Pseudonodosaria vulgata			3	2		
Vaginulina listi						
Vaginulina simplex			1			6
Lingulina tenera collenoti						
Lingulina tenera occidentalis					1	
Lingulina tenera subsp. A			30	11		5
Lingulina tenera pupa			19	3		
Lingulina tenera substriata						
Lingulina tenera tenera			136	152	74	50
Lingulina tenera tenuistriata						
Eoguttulina liassica						3
Eoguttulina simplex	2		1	5		
Spirillina infima	2		3		7	13
Brizalina liassica						
Reinholdella dreheri						
Reinholdella macfadyeni		63		3	5	6
Reinholdella pachyderma			18		1	
Reinholdella? planiconvexa						
Sample Totals	**273**	**236**	**301**	**303**	**302**	**293**

Species / Samples	TB 6	TB 22	TB 26	TB 29	TB 30	QTX 6
Lagenammina jurassica		1	2	1	8	
Lagena aphela						
Ammodiscus siliceous						
Ammobaculites fontinensis						
Haplophragmoides barrowensis						
Haplophragmoides kingakensis	12				12	
Thurammina jurensis						
Trochammina canningensis						
Trochammina occulta	23					
Trochammina sablei						
Trochammina topagorukensis						
Opthalmidium liascum		1	1	1		
Opthalmidium macfadyeni						
Nodosaria dispar			1			
Nodosaria fontinensis		2	2			
Nodosaria kuhni						
Nodosaria mitis						
Nodosaria metensis						
Nodosaria nitidana						
Nodosaria simplex						
Citharina colleizi						
Dentalina matutina						2
Dentalina irregularis						
Dentalina pseudocommunis		2	8	4	3	6
Dentalina terquemi				2	1	
Dentalina tortilis						
Dentalina varians				1		
Dentalina vetustissima			3			
Dentalina vetusta	8	3	10			
Astacolus pauperatus		3	8			
Astacolus pediacus						
Astacolus primus						
Astacolus / Vaginulinopsis speciosa						
Planularia inaequistriata						
Planularia protracta						3
Frondicularia terquemi bicostata						
Frondicularia terquemi muelensis						
Frondicularia terquemi sulcata						
Frondicularia terquemi subsp. B						
Frondicularia terquemi terquemi						
Lenticulina d'Orbigny						
Lenticulina foveolata				13		
Lenticulina muensteri muensteri		173	170	88	55	
Lenticulina muensteri acutiangulata	30					
Lenticulina muensteri polygonata	45	1		10		
Lenticulina muensteri subalata		35	29	36	125	
Lenticulina varians		19	7	34	9	1
Marginulina alata						
Marginulina prima insignis						
Marginulina prima interrupta						
Marginulina prima praerugosa						
Marginulina prima prima						
Marginulina prima rugosa						
Pseudonodosaria vulgata						
Vaginulina listi						
Vaginulina simplex						
Lingulina tenera collenoti						
Lingulina tenera occidentalis						
Lingulina tenera subsp. A						
Lingulina tenera pupa						
Lingulina tenera substriata						
Lingulina tenera tenera	40					3
Lingulina tenera tenuistriata						9
Eoguttulina liassica	10		7			
Eoguttulina simplex		3				
Spirillina infima		3	2			
Brizalina liassica	50					
Reinholdella dreheri						
Reinholdella macfadyeni	23	28	48	31	85	
Reinholdella pachyderma	60					
Reinholdella? planiconvexa						
Sample Totals	**301**	**274**	**298**	**221**	**298**	**24**

Species / Samples	QTX 10	EQH 13	QTX 9	EQH 10	EQH 8	EQH 4
Lagenammina jurassica				3		13
Lagena aphela						
Ammodiscus siliceous						
Ammobaculites fontinensis						
Haplophragmoides barrowensis						
Haplophragmoides kingakensis						
Thurammina jurensis						
Trochammina canningensis						
Trochammina occulta						
Trochammina sablei						
Trochammina topagorukensis						
Opthalmidium liascum						
Opthalmidium macfadyeni						
Nodosaria dispar						
Nodosaria fontinensis						
Nodosaria kuhni	2					
Nodosaria mitis						
Nodosaria metensis						
Nodosaria nitidana		2				
Nodosaria simplex		8	6	10	8	6
Citharina colleizi						
Dentalina matutina	35	16	17	5	6	8
Dentalina irregularis						
Dentalina pseudocommunis				9		6
Dentalina terquemi						
Dentalina tortilis						
Dentalina varians	3	19	8	4	32	60
Dentalina vetustissima						
Dentalina vetusta						
Astacolus pauperatus						
Astacolus pediacus						
Astacolus primus						
Astacolus / Vaginulinopsis speciosa	5	21	36			
Planularia inaequistriata	77	48	46	33	8	1
Planularia protracta		12	6	24	30	14
Frondicularia terquemi bicostata						
Frondicularia terquemi muelensis	11					
Frondicularia terquemi sulcata		48	38	10	31	6
Frondicularia terquemi subsp. B						
Frondicularia terquemi terquemi						
Lenticulina d'Orbigny						
Lenticulina foveolata						
Lenticulina muensteri muensteri						
Lenticulina muensteri acutiangulata						
Lenticulina muensteri polygonata						
Lenticulina muensteri subalata						
Lenticulina varians	10	6		8	1	4
Marginulina alata						
Marginulina prima insignis						
Marginulina prima interrupta						
Marginulina prima praerugosa				24	16	
Marginulina prima prima	48	6				
Marginulina prima rugosa						
Pseudonodosaria vulgata	2	2	1			
Vaginulina listi						
Vaginulina simplex						
Lingulina tenera collenoti						
Lingulina tenera occidentalis						
Lingulina tenera subsp. A						
Lingulina tenera pupa						
Lingulina tenera substriata			2			
Lingulina tenera tenera	147	94	36	151	162	4
Lingulina tenera tenuistriata		20	23	39		
Eoguttulina liassica						
Eoguttulina simplex						60
Spirillina infima						
Brizalina liassica						
Reinholdella dreheri						
Reinholdella macfadyeni						
Reinholdella pachyderma						
Reinholdella? planiconvexa						
Sample Totals	**340**	**302**	**219**	**320**	**294**	**182**

Species / Samples	EQH 24	QTX 2/4	QTX 2/11	QTX 2/2	RBH/B/4	RBH/1/3
Lagenammina jurassica		11				16
Lagena aphela						
Ammodiscus siliceous					1	2
Ammobaculites fontinensis						
Haplophragmoides barrowensis						
Haplophragmoides kingakensis						
Thurammina jurensis						
Trochammina canningensis						
Trochammina occulta						
Trochammina sablei						
Trochammina topagorukensis						
Opthalmidium liascum						
Opthalmidium macfadyeni						
Nodosaria dispar						
Nodosaria fontinensis						12
Nodosaria kuhni			3			
Nodosaria mitis						
Nodosaria metensis						
Nodosaria nitidana						
Nodosaria simplex		13	8	13		
Citharina colleizi						
Dentalina matutina					80	34
Dentalina irregularis						
Dentalina pseudocommunis						18
Dentalina terquemi					11	6
Dentalina tortilis						
Dentalina varians	11	16	14			7
Dentalina vetustissima						
Dentalina vetusta						
Astacolus pauperatus					6	
Astacolus pediacus			14			
Astacolus primus						
Astacolus / Vaginulinopsis speciosa		33				
Planularia inaequistriata			24			
Planularia protracta	2	39		20		
Frondicularia terquemi bicostata					13	
Frondicularia terquemi muelensis					3	3
Frondicularia terquemi sulcata		28	16	21	8	3
Frondicularia terquemi subsp. B						
Frondicularia terquemi terquemi						
Lenticulina d'Orbigny						
Lenticulina foveolata						
Lenticulina muensteri muensteri					49	14
Lenticulina muensteri acutiangulata						
Lenticulina muensteri polygonata						
Lenticulina muensteri subalata						
Lenticulina varians	36	22	44	12	12	4
Marginulina alata						
Marginulina prima insignis						
Marginulina prima interrupta						
Marginulina prima praerugosa			38			
Marginulina prima prima					79	4
Marginulina prima rugosa						
Pseudonodosaria vulgata					1	2
Vaginulina listi						
Vaginulina simplex						
Lingulina tenera collenoti			6			
Lingulina tenera occidentalis						
Lingulina tenera subsp. A						
Lingulina tenera pupa						
Lingulina tenera substriata						
Lingulina tenera tenera	46	73	84	86		13
Lingulina tenera tenuistriata	254	30	26	76		1
Eoguttulina liassica			22	31		
Eoguttulina simplex	17	36		24		
Spirillina infima						
Brizalina liassica						
Reinholdella dreheri						
Reinholdella macfadyeni				12	2	14
Reinholdella pachyderma						
Reinholdella? planiconvexa						
Sample Totals	**366**	**301**	**299**	**295**	**265**	**153**

Appendix 3 - Geochemical Data

SAMPLE	**Weight**	**height above base**	**SAMPLE No.**	**Al (ppm)**	**Ca (ppm)**	**Ba (ppm)**
HFS-B-1		85.9		236375	7081	754
HFS-B-2		85.4		223277	6237	955
HFS-B-3		84.4		262515	41575	795
HFS-B-4		83.4		236042	10856	780
HFS-B-5		83		288101	8683	1006
HFS-B-6		82.5		288489	8814	868
HFS-B-7mean		82.2		257021	70084	831
FOX/1/8	0.50026	82	36A	273620	8548	824
FOX/1/7	0.49995	81.4	9A	229163	9890	1005
FOX/1/6	0.50076	80.8	34A	265921	7466	803
FOX/1/5	0.50022	80.1	28A	267212	5344	874
FOX/1/4	0.50095	79.7	14A	248065	24375	6159
FOX/1/3	0.50011	79.3	33A	274305	20698	844
FOX/1/2	0.50029	78.9	31A	262153	17979	954
FOX/1/1	0.50006	78	32A	271317	12059	1136
HFS-C-1		77.5		252692	16642	1021
HFS-C-2		76.5		268454	25873	863
HFS-C-3mean		75.7		282107	14317	800
HFS-C-4		74.7		311355	8164	818
HFS-C-5		74.2		312077	7376	647
HFS-C-6		73.7		329171	12527	838
HFS-C-7		72.8		294206	8127	656
HFS-C-8A		71.9		280442	8382	658
HFS-C-8B		71.9		298479	18	32
HFS-C-9mean		70.8		277028	15512	639
HFS-C-10mean		69.8		275502	8719	790
FOX/2/3	0.50045	68	30A	281147	7671	743
FOX/2/2	0.49965	66.9	49A	286123	5340	1559
FOX/2/1	0.50022	66	13A	288911	14365	1828
FOX/2/1	0.50014	66	48A	293981	3959	1457
HFS-D-8mean		56.7		265956	51261	754
HFS-D-7mean		55.9		246106	35503	822
HFS-D-6		55		241703	27825	876
HFS-D-5		54		231047	35615	796
HFS/1/7	0.49992	53.4	20A	262347	38598	2342
HFS/1/5	0.50042	53.3	56A	258570	52015	894
HFS/1/4	0.50094	52.8	11A	249374	33404	863
HFS/1/3	0.49992	52	12A	271594	45232	2051
HFS/1/2	0.50047	51.5	66A	278626	13454	924
HFS/1/1	0.50067	51	65A	281826	8943	803
SN-7-47		50.3		246642	8840	723
HFS-D-1mean		50		274503	24611	842
HFS-D-2		49		218892	20711	759
SN-6-47mean		48.8		267982	5082	1181
HFS-D-3		48.5		260351	10703	924
SN/6/47	0.50028	48.3	46A	279836	5715	1014
HFS-D-4		48.1		283938	17215	783
SN-3-45		46.2		287157	15967	736
SN/2/45	0.50086	45.3	60A	282923	15852	1364
SN/14/45	0.50022	43.8	29A	250135	40685	794
SN/15/43	0.49992	41.9	41A	254205	41312	734
SN/19/43	0.5004	39.8	45A	246430	55733	763
PKS/2/4	0.50014	39	58A	255199	48829	824
PKS/2/5	0.50065	38	52A	249719	54701	853
PKS/2/3	0.49995	36	63A	272935	24022	985

SAMPLE	Weight	height above base	SAMPLE No.	Al (ppm)	Ca (ppm)	Ba (ppm)
SN/20/43	0.50067	35.8	44A	265567	73066	1024
PKS/2/2	0.50061	35	64A	220329	118646	1174
SN-17-43		34.7		220280	74365	673
PKS/2/1	0.50059	34	62A	251255	61835	833
RB-2-41		34		216284	114135	625
SN-16-43		33.6		228105	47838	669
SE-1-41		33		245366	38308	724
SE-2-41		32.4		210179	44478	614
PMG/1/19	0.5002	31.5	10A	259488	18083	683
PMG/1/18	0.48416	31.1	17A	226777	116450	944
PMG/1/17	0.39228	31	8A	204956	84160	6533
PM6/1/16	0.49973	30.7	3A	200907	59327	513
PMG/1/15	0.49994	30.1	7A	199014	106543	1035
PMG/1/14	0.50049	29.3	23A	173896	167570	462
PM6/1/13	0.4999	29.1	1A	109868	244967	392
PMG/1/1	0.50019	29	22A	95640	414204	432
PM6/1/2	0.50013	28.5	2A	147998	180953	613
PMG/1/7	0.5002	28.5	6A	148279	217496	693
PMG/1/8	0.50003	28.2	53A	192848	122201	1819
PMG/1/3	0.49965	27.9	21A	200537	128730	915
PM-5-38		27.8		185204	97013	303
PMG/1/9	0.49994	27.5	4A	196803	77696	1437
PMG/1/4	0.50071	27.05	5A	189977	93935	4837
PMG/1/5	0.4999	26.5	24A	193200	142035	935
PMG-C-5mean		26.3		181929	122276	859
PM-3-35		25.2		175658	56910	633
PMG/1/6	0.50088	25	35A	178074	78152	652
PMG/1/11	0.49973	24.65	16A	186227	87080	654
PMG/1/10	0.50036	24.3	26A	194629	35150	542
PM-1-34		24		113997	282867	513
PMG/1/12	0.50066	23.8	27A	205753	42656	763
PMG-C-4		23.6		145355	41588	557
PMG-C-4		23.1		173105	42388	562
PMG-C-3		22.7		198191	17220	558
PMG-C-3		22.7		189255	16422	571
PMG-C-2		22		247974	15659	670
PMG-C-1		21.6		208847	33196	652
PM-12-32mean		21.2		169941	35966	531
PMG-B-3		20.5		184871	46120	756
PMG-B-2		20.3		210567	31062	710
PMG-B-1		19.8		265290	31830	625
PM/14/31	0.50067	19.5	67A	193806	36132	572
PM/15/31	0.5005	19	50A	246079	30421	683
PM/16/31	0.49992	17.9	18A	245862	19802	724
PM/18/27	0.5006	16	55A	259080	17065	974
BRW/1/11	0.49991	10.5	40A	254713	10454	824
BRW-1-9		10.2		234432	13009	896
BRW-1-8		9.6		263292	14702	867
BRW/1/12	0.50023	9.1	51A	143749	76345	452
BRW-1-7		8.4		219003	10376	724
BRW-1-6		7.9		174992	19245	1032
BRW/1/3	0.50077	7.4	39A	146304	7566	542
BRW/1/2	0.50034	7	38A	187004	5152	110
BRW/3/2	0.50052	6.95	15A	196876	17670	1104
BRW/3/1	0.46149	5.5	25A	224306	46712	817
BRW-2-4		1.6		229382	3415	430
BRW-2-3		1.3		195249	84061	600
BRW/2/2	0.5001	0.8	59A	168103	58278	432
BRW-2-1		0.5		203574	4008	766
PM-9-40				141359	334612	528

SAMPLE	Mn (ppm)	Fe (ppm)	Sr (ppm)	Mg (ppm)	Mn/Al	Ca/Al	Ba/Al	Sr/Al	Fe/Al	Mg/Al
HFS-B-1	198	55638		24706	0.0008	0.0300	0.0032		0.2354	0.1045
HFS-B-2	211	87532		22668	0.0009	0.0279	0.0043		0.3920	0.1015
HFS-B-3	317	101090		24565	0.0012	0.1584	0.0030		0.3851	0.0936
HFS-B-4	284	102565		25463	0.0012	0.0460	0.0033		0.4345	0.1079
HFS-B-5	220	115913		27070	0.0008	0.0301	0.0035		0.4023	0.0940
HFS-B-6	207	147455		25213	0.0007	0.0306	0.0030		0.5111	0.0874
HFS-B-7m	292	233581		23638	0.0011	0.2727	0.0032		0.9088	0.0920
FOX/1/8	321	150973	382	28929	0.0012	0.0312	0.0030	0.0014	0.5518	0.1057
FOX/1/7	201	96289	3518	23419	0.0009	0.0432	0.0044	0.0154	0.4202	0.1022
FOX/1/6	171	121922	341	26592	0.0006	0.0281	0.0030	0.0013	0.4585	0.1000
FOX/1/5	201	143652	342	25315	0.0008	0.0200	0.0033	0.0013	0.5376	0.0947
FOX/1/4	211	118967	451	30394	0.0008	0.0983	0.0248	0.0018	0.4796	0.1225
FOX/1/3	251	112535	442	27531	0.0009	0.0755	0.0031	0.0016	0.4103	0.1004
FOX/1/2	372	142627	412	30133	0.0014	0.0686	0.0036	0.0016	0.5441	0.1149
FOX/1/1	161	122595	412	26629	0.0006	0.0444	0.0042	0.0015	0.4519	0.0981
HFS-C-1	251	160311		25821	0.0010	0.0659	0.0040		0.6344	0.1022
HFS-C-2	206	171340		25643	0.0008	0.0964	0.0032		0.6382	0.0955
HFS-C-3m	218	156025		26145	0.0008	0.0511	0.0028		0.5529	0.0927
HFS-C-4	198	150757		25492	0.0006	0.0262	0.0026		0.4842	0.0819
HFS-C-5	239	157220		25293	0.0008	0.0236	0.0021		0.5038	0.0810
HFS-C-6	360	262946		29783	0.0011	0.0381	0.0025		0.7988	0.0905
HFS-C-7	243	146542		25607	0.0008	0.0276	0.0022		0.4981	0.0870
HFS-C-8A	214	134529		25675	0.0008	0.0299	0.0023		0.4797	0.0916
HFS-C-8B	18	149562		50	0.0001	0.0001	0.0001		0.5011	0.0002
HFS-C-9m	254	162980		25654	0.0009	0.0562	0.0023		0.5877	0.0929
HFS-C-10n	187	178716		24067	0.0007	0.0317	0.0029		0.6544	0.0875
FOX/2/3	161	130533	442	25705	0.0006	0.0273	0.0026	0.0016	0.4643	0.0914
FOX/2/2	161	128831	443	26148	0.0006	0.0187	0.0054	0.0015	0.4503	0.0914
FOX/2/1	181	123561	472	31141	0.0006	0.0497	0.0063	0.0016	0.4277	0.1078
FOX/2/1	261	131015	362	27027	0.0009	0.0135	0.0050	0.0012	0.4457	0.0919
HFS-D-8m	271	113981		23819	0.0010	0.1935	0.0028		0.4271	0.0898
HFS-D-7m	244	67908		25480	0.0010	0.1451	0.0034		0.2822	0.1038
HFS-D-6	285	113173		25090	0.0012	0.1151	0.0036		0.4682	0.1038
HFS-D-5	244	164666		24740	0.0011	0.1541	0.0034		0.7127	0.1071
HFS/1/7	281	124137	493	25732	0.0011	0.1471	0.0089	0.0019	0.4732	0.0981
HFS/1/5	372	134155	502	25506	0.0014	0.2012	0.0035	0.0019	0.5188	0.0986
HFS/1/4	301	169827	411	30394	0.0012	0.1340	0.0035	0.0016	0.6810	0.1219
HFS/1/3	472	135295	452	38598	0.0017	0.1665	0.0075	0.0017	0.4981	0.1421
HFS/1/2	221	111751	361	27411	0.0008	0.0483	0.0033	0.0013	0.4011	0.0984
HFS/1/1	201	116625	361	27199	0.0007	0.0317	0.0028	0.0013	0.4138	0.0965
SN-7-47	205	96102		25740	0.0008	0.0358	0.0029		0.3896	0.1044
HFS-D-1m	289	123851		26735	0.0011	0.0911	0.0031		0.4617	0.0990
HFS-D-2	239	106780		26354	0.0011	0.0946	0.0035		0.4878	0.1204
SN-6-47m	188	82438		26252	0.0007	0.0190	0.0044		0.3076	0.0980
HFS-D-3	247	119636		26901	0.0009	0.0411	0.0036		0.4595	0.1033
SN/6/47	160	104060	352	27622	0.0006	0.0204	0.0036	0.0013	0.3719	0.0987
HFS-D-4	236	138182		27785	0.0008	0.0606	0.0028		0.4867	0.0979
SN-3-45	212	104040		25709	0.0007	0.0556	0.0026		0.3623	0.0895
SN/2/45	211	112668	401	27991	0.0007	0.0560	0.0048	0.0014	0.3982	0.0989
SN/14/45	291	163743	452	25214	0.0012	0.1627	0.0032	0.0018	0.6546	0.1008
SN/15/43	261	125243	432	25632	0.0010	0.1625	0.0029	0.0017	0.4927	0.1008
SN/19/43	572	160872	753	27716	0.0023	0.2262	0.0031	0.0031	0.6528	0.1125
PKS/2/4	311	134331	653	25218	0.0012	0.1913	0.0032	0.0026	0.5264	0.0988
PKS/2/5	311	169022	753	24089	0.0012	0.2191	0.0034	0.0030	0.6768	0.0965
PKS/2/3	332	127547	482	26736	0.0012	0.0880	0.0036	0.0018	0.4673	0.0980

SAMPLE	**Mn (ppm)**	**Fe (ppm)**	**Sr (ppm)**	**Mg (ppm)**	**Mn/Al**	**Ca/Al**	**Ba/Al**	**Sr/Al**	**Fe/Al**	**Mg/Al**
SN/20/43	331	136798	512	36232	0.0012	0.2751	0.0039	0.0019	0.5151	0.1364
PKS/2/2	683	154080	1124	27002	0.0031	0.5385	0.0053	0.0051	0.6993	0.1226
SN-17-43	260	144083		23788	0.0012	0.3376	0.0031		0.6541	0.1080
PKS/2/1	361	134511	753	25497	0.0014	0.2461	0.0033	0.0030	0.5354	0.1015
RB-2-41	291	105516		23544	0.0013	0.5277	0.0029		0.4879	0.1089
SN-16-43	239	118371		24874	0.0010	0.2097	0.0029		0.5189	0.1090
SE-1-41	251	126099		24871	0.0010	0.1561	0.0030		0.5139	0.1014
SE-2-41	261	141273		24548	0.0012	0.2116	0.0029		0.6722	0.1168
PMG/1/19	261	150187	362	24211	0.0010	0.0697	0.0026	0.0014	0.5788	0.0933
PMG/1/18	363	138868	913	21588	0.0016	0.5135	0.0042	0.0040	0.6124	0.0952
PMG/1/17	218	107474	1114	19727	0.0011	0.4106	0.0319	0.0054	0.5244	0.0963
PM6/1/16	201	113325	322	18200	0.0010	0.2953	0.0026	0.0016	0.5641	0.0906
PMG/1/15	261	111568	442	17891	0.0013	0.5354	0.0052	0.0022	0.5606	0.0899
PMG/1/14	542	195080	693	19980	0.0031	0.9636	0.0027	0.0040	1.1218	0.1149
PM6/1/13	573	148066	9047	15882	0.0052	2.2296	0.0036	0.0823	1.3477	0.1446
PMG/1/1	1567	116134	2170	22805	0.0164	4.3309	0.0045	0.0227	1.2143	0.2384
PM6/1/2	733	138553	955	28133	0.0050	1.2227	0.0041	0.0064	0.9362	0.1901
PMG/1/7	502	116835	1336	21097	0.0034	1.4668	0.0047	0.0090	0.7879	0.1423
PMG/1/8	533	174860	925	23616	0.0028	0.6337	0.0094	0.0048	0.9067	0.1225
PMG/1/3	523	148442	674	23634	0.0026	0.6419	0.0046	0.0034	0.7402	0.1179
PM-5-38	1602	632250		46242	0.0086	0.5238	0.0016		3.4138	0.2497
PMG/1/9	332	119308	513	25832	0.0017	0.3948	0.0073	0.0026	0.6062	0.1313
PMG/1/4	311	119626	492	22580	0.0016	0.4945	0.0255	0.0026	0.6297	0.1189
PMG/1/5	553	153595	553	22315	0.0029	0.7352	0.0048	0.0029	0.7950	0.1155
PMG-C-5m	451	147385	0	28387	0.0025	0.6720	0.0047		0.8100	0.1560
PM-3-35	449	150757		27775	0.0026	0.3240	0.0036		0.8582	0.1581
PMG/1/6	1033	168142	431	32103	0.0058	0.4389	0.0037	0.0024	0.9442	0.1803
PMG/1/11	1488	126698	493	34490	0.0080	0.4676	0.0035	0.0026	0.6803	0.1852
PMG/1/10	633	217024	331	25709	0.0033	0.1806	0.0028	0.0017	1.1151	0.1321
PM-1-34	373	98139		21331	0.0033	2.4814	0.0045		0.8609	0.1871
PMG/1/12	652	153562	391	26698	0.0032	0.2073	0.0037	0.0019	0.7463	0.1298
PMG-C-4	413	206676		23316	0.0028	0.2861	0.0038		1.4219	0.1604
PMG-C-4	422	228313		22993	0.0024	0.2449	0.0032		1.3189	0.1328
PMG-C-3	321	153215		22094	0.0016	0.0869	0.0028		0.7731	0.1115
PMG-C-3	329	171270		23964	0.0017	0.0868	0.0030		0.9050	0.1266
PMG-C-2	318	196981		22150	0.0013	0.0631	0.0027		0.7944	0.0893
PMG-C-1	389	139165		28626	0.0019	0.1590	0.0031		0.6664	0.1371
PM-12-32n	279	165404	0	20091	0.0016	0.2117	0.0031		0.9738	0.1183
PMG-B-3	352	224870		18248	0.0019	0.2495	0.0041		1.2164	0.0987
PMG-B-2	368	111908		23164	0.0017	0.1475	0.0034		0.5315	0.1100
PMG-B-1	338	208151		24068	0.0013	0.1200	0.0024		0.7846	0.0907
PM/14/31	512	158778	281	20876	0.0026	0.1864	0.0030	0.0015	0.8193	0.1077
PM/15/31	622	193470	382	27409	0.0025	0.1236	0.0028	0.0016	0.7862	0.1114
PM/16/31	342	117202	342	26536	0.0014	0.0805	0.0029	0.0014	0.4767	0.1079
PM/18/27	301	101584	391	29913	0.0012	0.0659	0.0038	0.0015	0.3921	0.1155
BRW/1/11	332	112580	362	30055	0.0013	0.0410	0.0032	0.0014	0.4420	0.1180
BRW-1-9	266	90974		29507	0.0011	0.0555	0.0038		0.3881	0.1259
BRW-1-8	272	101792		30434	0.0010	0.0558	0.0033		0.3866	0.1156
BRW/1/12	4581	459476	382	56756	0.0319	0.5311	0.0031	0.0027	3.1964	0.3948
BRW-1-7	316	122305		24354	0.0014	0.0474	0.0033		0.5585	0.1112
BRW-1-6	228	50229		20655	0.0013	0.1100	0.0059		0.2870	0.1180
BRW/1/3	1385	312175	171	12904	0.0095	0.0517	0.0037	0.0012	2.1337	0.0882
BRW/1/2	773	156473	251	22095	0.0041	0.0276	0.0006	0.0013	0.8367	0.1182
BRW/3/2	251	93167	281	29617	0.0013	0.0898	0.0056	0.0014	0.4732	0.1504
BRW/3/1	566	137959	381	26024	0.0025	0.2083	0.0036	0.0017	0.6150	0.1160
BRW-2-4	349	753712		44698	0.0015	0.0149	0.0019		3.2858	0.1949
BRW-2-3	334	166914		24308	0.0017	0.4305	0.0031		0.8549	0.1245
BRW/2/2	4964	612827	281	52852	0.0295	0.3467	0.0026	0.0017	3.6455	0.3144
BRW-2-1	247	278260		30381	0.0012	0.0197	0.0038		1.3669	0.1492
PM-9-40	400	86829		18048						

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HETTANGIAN TO SINEMURIAN (LOWER JURASSIC) SEA-LEVEL CHANGES AND PALAEOENVIRONMENTS: EVIDENCE FROM BENTHIC FORAMINIFERA AT EAST QUANTOXHEAD, WEST SOMERSET, U.K.

M. D. HYLTON

Hylton, M. D. 1999. Hettangian to Sinemurian (Lower Jurassic) sea-level change and palaeoenvironments: evidence from benthic foraminifera at East Quantoxhead, West Somerset, U.K. *Geoscience in south-west England*, **9**, 285-288.

The Hettangian to Sinemurian (Lower Jurassic) of the West Somerset coast, near East Quantoxhead, comprises an expanded fossiliferous sequence of alternations of thickly laminated mudstones, more homogenous mudstones and limestones.
During Hettangian times a broad shallow marine shelf sea was established over most of Britain and north-west Europe, colonised by a low (but gradually increasing) diversity foraminiferal fauna, related to the major transgressive pulse at the base of the Jurassic. Imposed upon this general trend of sea-level rise, with major pulses in the early Hettangian and early Sinemurian, were episodic falls of sea-level. While there is little facies evidence for a major sea-level drop around the end of the Hettangian at East Quantoxhead, it is notable that several index foraminifera become extinct at or near the top of the Hettangian Angulata Zone which is interpreted as evidence for a minor regression. Changes in foraminiferal assemblages from this Lower Jurassic section have been examined and are considered to be related to sea-level changes where transgressions mark the arrival of new species and subspecies (evolutionary appearances and/or migration) whereas regressions and times of lowered sea-level appear to equate to extinctions. Within these nodosariid-dominated foraminiferal populations, major variations in species and generic abundances are seen in taxa which are long ranging, suggesting controlling palaeoenvironmental factors. The predominance of the *Lingulina tenera* (Bornemann) plexus with associated *Lenticulina* and *Marginulina* species suggests inner to near shelf environments with periods of normal oxygen levels.

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INTRODUCTION

Palaeoecological interpretations of Jurassic foraminiferal assemblages are frequently problematic owing to the lack of direct Recent analogues due to drastic changes which took place in the nature of benthic shelf assemblages during the Cretaceous and Tertiary (Copestake and Johnson, 1989). These changes resulted in the replacement of nodosariids, which were dominant in the Jurassic (Gordon, 1970), by other families of Rotaliina; it has been established that nodosariids in the modern day occupy a deeper water setting

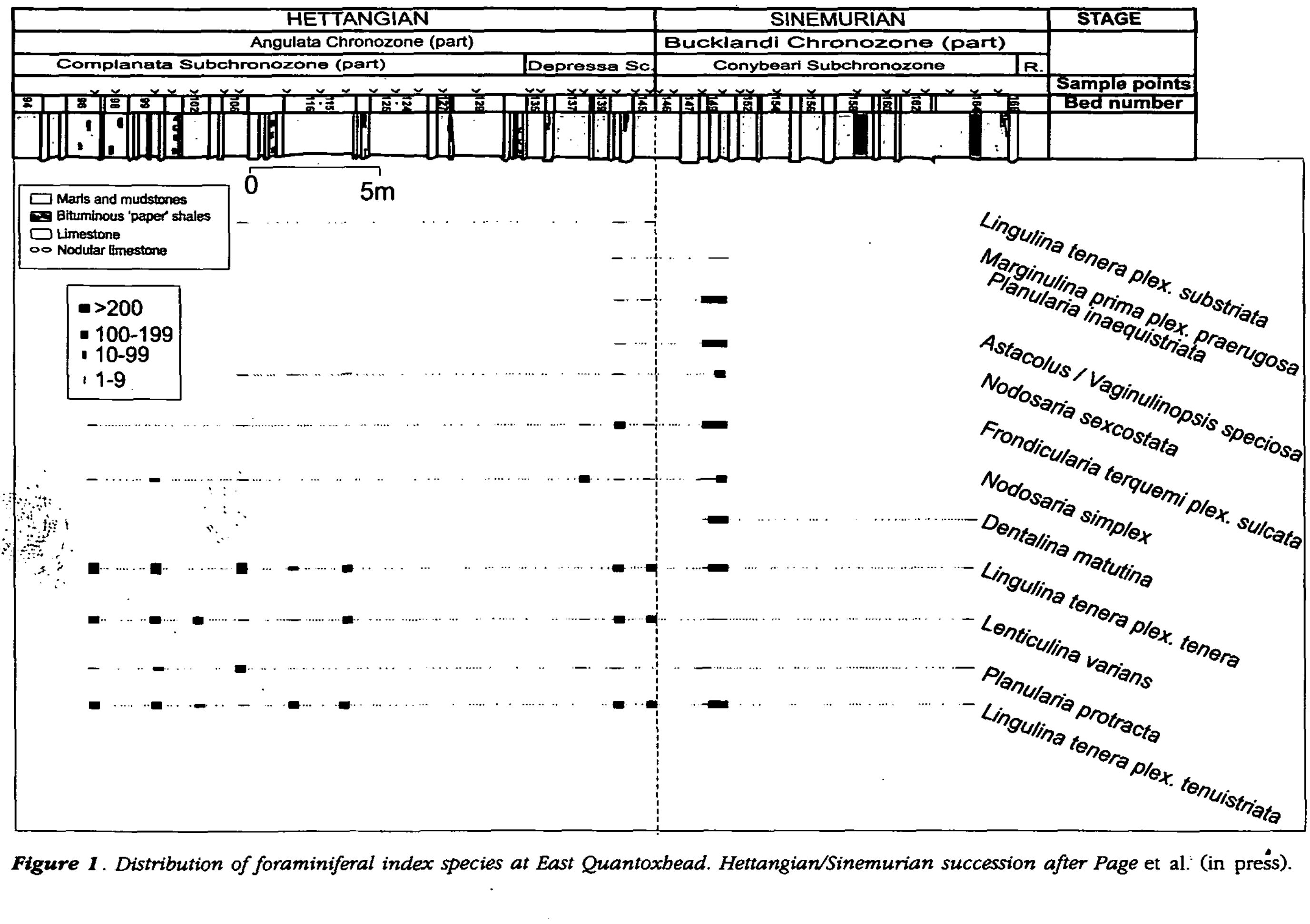

***Figure 1**. Distribution of foraminiferal index species at East Quantoxhead. Hettangian/Sinemurian succession after Page* et al. *(in press).*

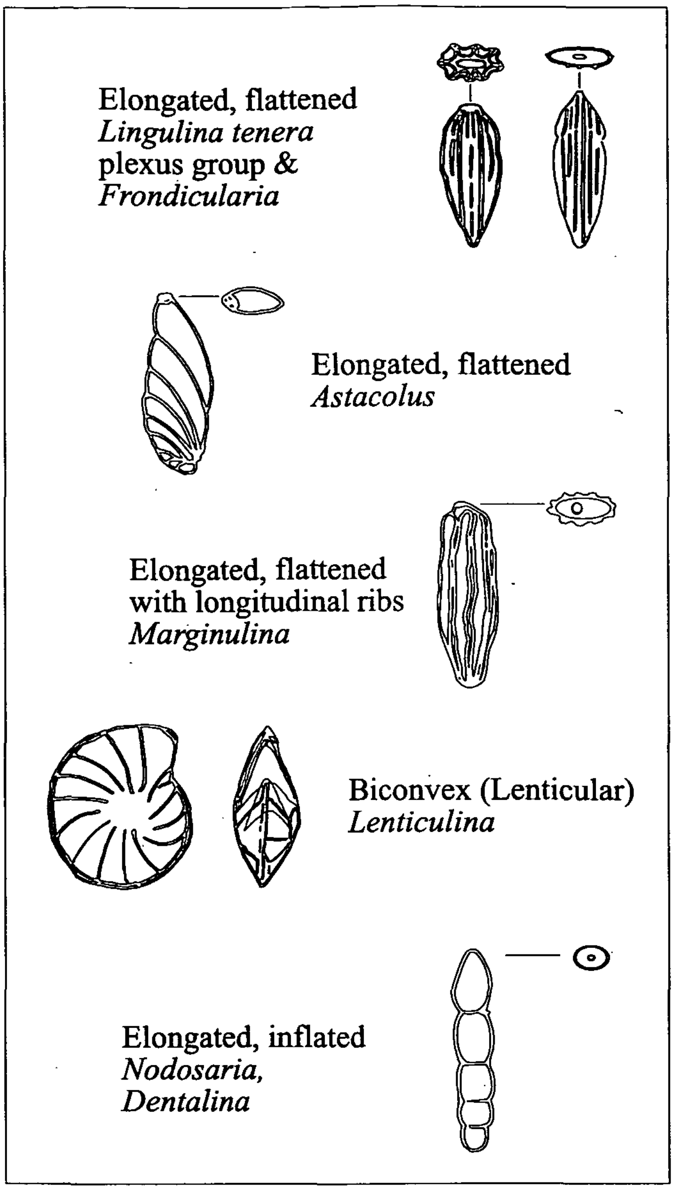

***Figure 2**. Palaeoenvironmentally significant morphogroups of benthic foraminifera recovered from East Quantoxhead.*

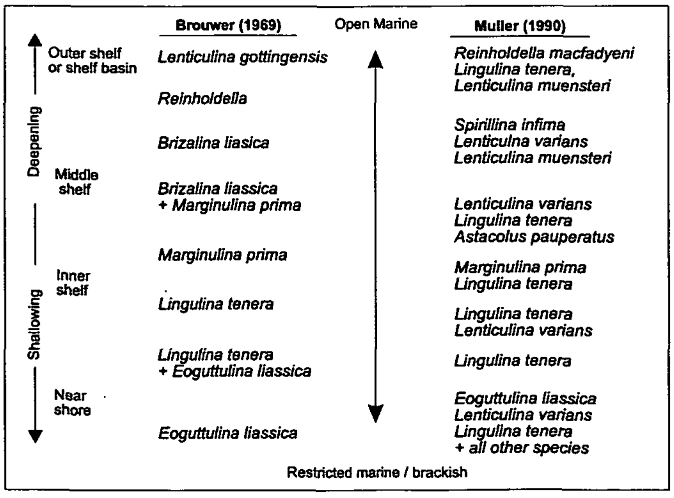

***Figure 3**. Benthic foraminiferal assemblages as Early Jurassic sea-level indicators.*

than in the Jurassic (Johnson, 1976). It is necessary, therefore, to establish environmental data on individual Lower Jurassic fossil species so that finer and more accurate palaeoecological analyses can be made.

The sedimentology, palaeontology and palaeogeography of the Lower Jurassic of southern Britain is well documented (e.g. Sellwood, 1972; Hallam, 1987; Warrington and Ivimey-Cook, 1995) and the exposure at East Quantoxhead presents an excellent opportunity to establish ecological data on individual Lower Jurassic foraminiferal species. This study expands upon the investigation of the correlation potential of foraminiferal faunas by Hylton (1998) as a contribution to the proposal of the section as a candidate "Global Stratotype Section and Point" for the base of the Sinemurian Stage (Page *et al. in press)*. As a result of this proposal the section at East Quantoxhead has been assessed for its macrofossil, microfossil, geochemical and magnetostratigraphical global correlation potential. More recently Hart and Hylton (this volume) have investigated the stratigraphical distribution of the ostracod fauna.

MATERIAL AND METHODS

The coastal exposures of the Hettangian - Sinemurian succession can be easily accessed from the village of East Quantoxhead on the West Somerset Coast. The typical marine sedimentary facies at this locality is an alternating limestone/shale sequence known as the Blue Lias Formation (Palmer, 1972). Comprehensive descriptions of the location, stratigraphy, macro- and microfossil groups of the succession can be found in Hart and Hylton (this volume); Hylton (1998); Page (1992, 1995) and Page *et al.* (*in press)*.

A total of 50 samples from the cliff and wave-cut platform have been collected from the levels marked on Figure 1. 200 gm of material from each sample was dissagragated using the techniques detailed in Hylton (1998). The foraminiferal fauna obtained was picked according to the methodology of this initial study and follows the same taxonomy.

Figure 1 lists the ranges of 11 stratigraphically useful index species and extends their known ranges at East Quantoxhead. While certain intervals remain barren, the lower and boundary levels of the section have yielded well preserved, diverse foraminiferal faunas which can be used to establish the palaeoenvironmental conditions at East Quantoxhead during this period.

LOWER JURASSIC FORAMINIFERA AS SEA-LEVEL INDICATORS

The foraminiferal assemblages at East Quantoxhead, and those of the Lower Jurassic in general, are characterised by combinations of a restricted number of species which constitute the bulk of the fauna. These smaller benthic foraminifera occur in assemblages dominated by certain forms, illustrated in Figure 2, of the elongate, flattened *Astacolus*, the uniserial, ribbed groups of *Lingulina tenera*, *Frondicularia* and *Marginulina*. Also present are a number of species of the long ranging genera *Lenticulina* and *Nodosaria*. These species can be considered as the main components of the assemblages.

While Lower Jurassic assemblages are dominated by the suborder lagenina, certain combinations of faunal main components appear repeatedly, with the exclusion of those main components from other combinations. In the change from one environment to another, one or more of the main components are usually replaced by others, consequently, different environments of deposition result in different combinations of main components. The statistical relationships between foraminiferal assemblages and depositional environment have been explored by Johnson (1975), Brouwer (1969) and Muller (1990). These latter two studies are summarised in Figure 3. The earliest study by Brouwer (1969) examined assemblages from north-west Europe while more recently Muller (1990) used statistical analysis

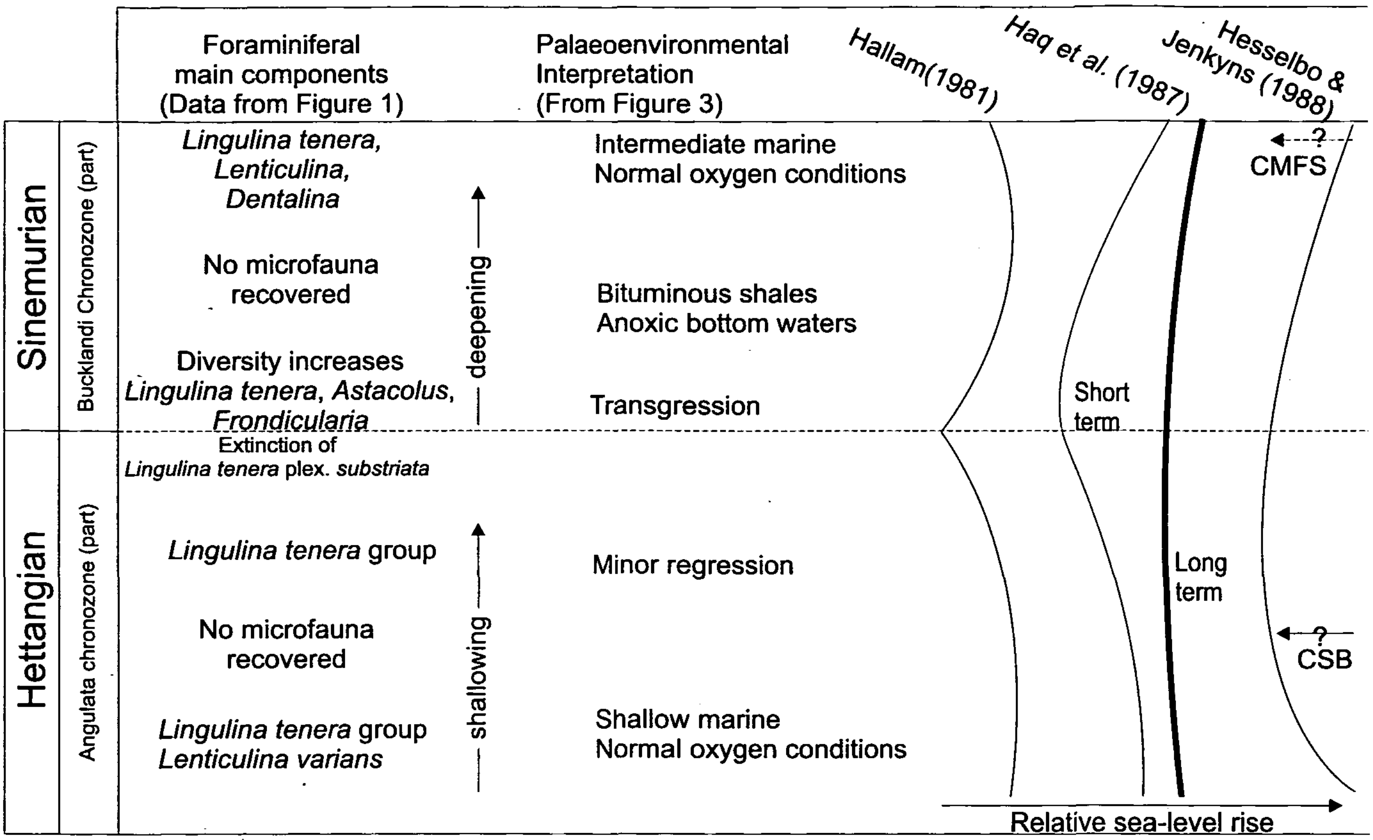

***Figure 4**. Interpretation of eustatic events and palaeoenvironments from foraminiferal evidence at East Quantoxhead. CMFS - Candidate maximum flooding surface, CSB - Candidate sequence boundary (after Hesselbo and Jenkyns, 1988).*

of foraminiferal assemblages from the U.K. Lower Jurassic to propose 'biofacies' groups and hence a depth distribution model. Put simply, it seems that the deeper shelf environments were dominated by *Lenticulina*, intermediate depths by the *Marginulina prima* group and shallower depths by the *Lingulina tenera* group.

PALAEOENVIRONMENTS AT EAST QUANTOXHEAD

During Hettangian times a broad shallow marine shelf sea was established over much of Britain and north-west Europe, colonised by a low (but gradually increasing) diversity foraminiferal fauna, resulting from the major transgressive pulse at the base of the Jurassic. Imposed upon this general trend of sea-level rise, with major pulses in the early Hettangian and early Sinemurian, were episodic falls of sea-level (Hallam, 1981).

Changes in foraminiferal assemblages are considered to be related to sea-level changes, in that well-documented transgressions mark the arrival of new species and subspecies (evolutionary appearances and/or migration) whereas regressions and times of lowered sea-level appear to equate to extinctions (Copestake and Johnson, 1981). Accordingly the foraminiferal data in Figure 1 can be used, in conjunction with published depth distributions (Figure 3), to construct a model of environmental change across the Hettangian - Sinemurian boundary at East Quantoxhead. The model in Figure 4 can then be compared with published sea-level curves of Hallam (1981), Haq *et al.* (1987) and Hesselbo and Jenkyns (1988).

Within the nodosariid-dominated foraminiferal populations of the Hettangian - Sinemurian section examined, major variations in species and generic abundances are seen in taxa which are long ranging, suggesting controlling palaeoenvironmental factors (Copestake and Johnson, 1989). The predominance of the *Lingulina tenera* (Bornemann) plexus with associated *Lenticulina* and *Marginulina* species in the lower part of the section suggests inner to near shelf environments with periods of normal oxygen levels.

Towards the boundary, there is a noticeable decline in abundances and diversity, eventually resulting in the extinction of *Lingulina tenera* plex. *substriata*. Indicative of a regressive phase, Copestake and Johnson (1989) also report that several index foraminifera become extinct at or near the top of the Angulata Zone at many European localities (*Lingulina tenera collenoti, L. tenera substriata, Frondicularia terquemi* subsp. A) while *Dentalina langi* both appeared and became extinct within the late Angulata Zone. An increase in diversity across the boundary indicates a return to deeper, oxygenated conditions, reflecting a transgressive event.

Hallam (1978) records a basal Sinemurian (early Bucklandi Zone) transgression, preceded by a late Hettangian regression. However, this event is only locally apparent in Europe, where for example, sandstones are abruptly replaced by marls and limestones, in north-east France and southern Germany. The Blue Lias facies of southern England, however, continues across the stage boundary with only subtle changes at most. Hallam (1981) suggests, therefore, that if any eustatic event took place at all, it must have been only a minor event. More recently, Hesselbo and Jenkyns (1988) argue for a mid-Angulata regression followed by a Bucklandi transgression. The subtle changes in the foraminiferal assemblages at East Quantoxhead would seem to support the case for this interpretation.

The higher levels of the section at East Quantoxhead contain darker, more organic rich marls and shales (Figures 1 and 4) representing low-oxygen bottom water conditions which lack any benthic fauna, including foraminifera. In a study of the Blue Lias of southern Britain, Weedon (1986) proposes a hemipelagic shelf regime being supplied with clay from rivers. The cycles in bottom-water oxygenation, which affected organic carbon contents were associated with changes in the clay-to-carbonate mud ratio. These changes are ultimately believed to be caused by Milankovitch driven climatic cycles changing sedimentation rates and indirectly affecting primary productivity through increases of nutrients in runoff water. The anoxic conditions may then have resulted from the additional organic matter. Bottom-water anoxia and increased clay supply will affect benthic assemblages and could be responsible for the barren intervals seen in the foraminiferal and ostracod faunas (Hart and Hylton, this volume).

CONCLUSIONS

The ranges of identified foraminiferal taxa at East Quantoxhead have been extended and provide further data to assist in the definition of the base of the Sinemurian stage. This data can be used to interpret the palaeoenvironmental conditions at East Quantoxhead during this interval of the Lower Jurassic.

While there is little facies evidence for a major sea-level drop around the end of the Hettangian at East Quantoxhead interpretation of foraminiferal assemblages provide evidence for a minor regression. Following this regression at the end of the Hettangian a transgressive event coincides with the deposition of organic-rich mudstones associated with the periodic development of low-oxygen bottom waters. It is also notable, from other studies, that several index foraminifera become extinct at or near the top of the Hettangian Angulata Zone.

The changes in foraminiferal assemblages are considered to reflect sea-level changes where transgressions mark the arrival of new species whereas regressions and times of lowered sea-level appear to equate to extinctions. Interpreted palaeoenvironmental ranges of Lower Jurassic foraminiferal species however still remain broad, varying between the inner and outer shelf and further work to establish environmental parameters of these species is required.

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HETTANGIAN TO SINEMURIAN OSTRACOD FAUNAS FROM EAST QUANTOXHEAD, WEST SOMERSET.

M.B. HART AND M. D. HYLTON

Hart, M. B. and Hylton, M.D. 1999. Hettangian to Sinemurian ostracod faunas from East Quantoxhead, West Somerset. *Geoscience in South-West England*, **9**, 289-296.

The Hettangian to Sinemurian (Lower Jurassic) succession has been investigated for its ostracod fauna. The marine assemblages from this part of the Lower Jurassic succession are of low diversity, dominated by the genus *Ogmoconcha* Triebel, 1941. The stratigraphica distribution of the known taxa, although distinctive, do not appear to provide a diagnostic tool for recognition of the base of the Sinemurian Stage. The data generated by this work do, however, provide additional evidence that the East Quantoxhead succession is a suitable GSSP for the base of the Sinemurian Stage.

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INTRODUCTION

The Sinemurian Stage was initially defined (d'Orbigny, 1942) as the lowest stage of the Lower Jurassic and was named after Semur-en-Auxois in Burgundy. Subsequently Renevier (1864) redefined the Sinemurian by separating the lower part of d'Orbigny's original unit as the Hettangian. By tradition (Arkell, 1933) the Sinemurian is now the 2nd stage of the Jurassic. Recent work (Page, 1992, 1995) on the distribution of the ammonites in the succession has indicated (Page *et al., in press*) that the succession at Semur-en-Auxois, and elsewhere in South-east France, may be significantly thinner than the succession near the village of East Quantoxhead, Somerset. The Somerset succession has recently (August, 1998) been proposed (Page *et al. in press*) as a candidate "Global Stratotype Section and Point" (GSSP) for the base of the Sinemurian Stage. In order to fully assess the utility of the East Quantoxhead succession as a GSSP data are being gathered on all macrofossil, microfossil and microfloral groups as well as geochemical, sedimentological and magnetostratigraphical information. Work by Hylton (1998) on the foraminifera is here supported by work on the ostracod faunas using the same samples.

THE SUCCESSION

The coastal succession of the Hettangian - Sinemurian transition is exposed on the foreshore immediately to the east of Quantock's Head (Figure 1) on the West Somerset coast. The nearest access point is by means of a minor road which runs northwards from the village of Kilve to a car park near the beach. Access to the sampled succession is best obtained by following the coastal path westwards for 0.5 km and then descending to the foreshore by some metal stairs which are actually built across the boundary section. The succession of the Lias Group can then be followed both east and west along the sea cliffs as well as the foreshore. There are numerous small faults in the succession, but it is possible to identify the lithological succession of Palmer (1972) and Whittaker and Green (1983) with little difficulty. The sampled succession is shown in Figure 2, although it must be pointed out that only samples yielding ostracods are marked. The whole succession has been sampled but many of the samples, especially in the upper part of the section, are barren of both ostracods and foraminifera (see Hylton, 1998). Samples collected for this work weighed approximately 200 gm and were prepared as described by Hylton (1998). In most clay successions this method should yield reliable ostracod assemblages, especially as most of the material is preserved as distinct carapaces, rather than separated valves. The latter can often be broken, especially in the case of delicate taxa such as *Polycope*.

MATERIALS AND METHODS

A number of samples have been collected from the succession (see Hylton, 1998, fig.3 for locations) but, unfortunately, a number of these proved to be barren of ostracods. The samples yielding faunas are indicated in Figure 2. As indicated by Hylton (1998), around 200 grams of sediment was processed for each sample using standard preparation techniques. The raw sample was broken into small fragments (5 - 10 mm diameter) and then dried in an oven at 60° for approximately 12 hours. The sample was then soaked in white spirit for several hours under a fume hood and the excess poured off. The sample was then soaked in distilled water for around eight hours. If the sample had not completely broken down it was bolied gently in a solution of washing soda prior to sieving through a 74 µm sieve under a gentle jet of water. The process was repeated if unsuccessful at a first attempt. The sieve residue was gently dried and stored in plastic phials. All specimens from the full range of size fractions were picked from the residue and inspected. All specimens remain in the collections of the University of Plymouth.

TAXONOMY

The fauna described in this investigation has not been subjected to a thorough taxonomic analysis and only key texts are cited in the reference and synonymy lists. There is little published work on Lower Jurassic Ostracoda of the UK. In the last century the works of Jones (1872, 1894) and Blake (in Tate and Blake, 1876) contain a number of original descriptions of taxa. Aside from brief mentions in papers on other aspects of the succession the next major works on the Lower Jurassic of the UK are those of Field (1966), Bate and Coleman (1968) and Lord (1971, 1972, 1974 and 1978). A number of unpublished theses (Field, 1968; Clark, 1969; Park, 1985) have been generated and while a number of authors (e.g., Lord, 1978) have made use of these data in their publications, much of this valuable information remains unavailable. While Field (1968) produced a valuable documentation of the ostracod succession of the Dorset coast (sampled bed-by-bed) there has been no previous attempt to compare his data with the succession in West Somerset. In general we have found faunas from the West Somerset succession much less diverse and this is probably due to differences in depositional environment between the two areas; the Somerset succession contains more, very dark, organic-rich mudstones.

Although the following data are presented as a taxonomic account the justification of the taxa reported is simply to enable the use of the identified species in the range chart (Figure 2). The classification followed is that of the Treatise (Benson *et al.*, 1961).

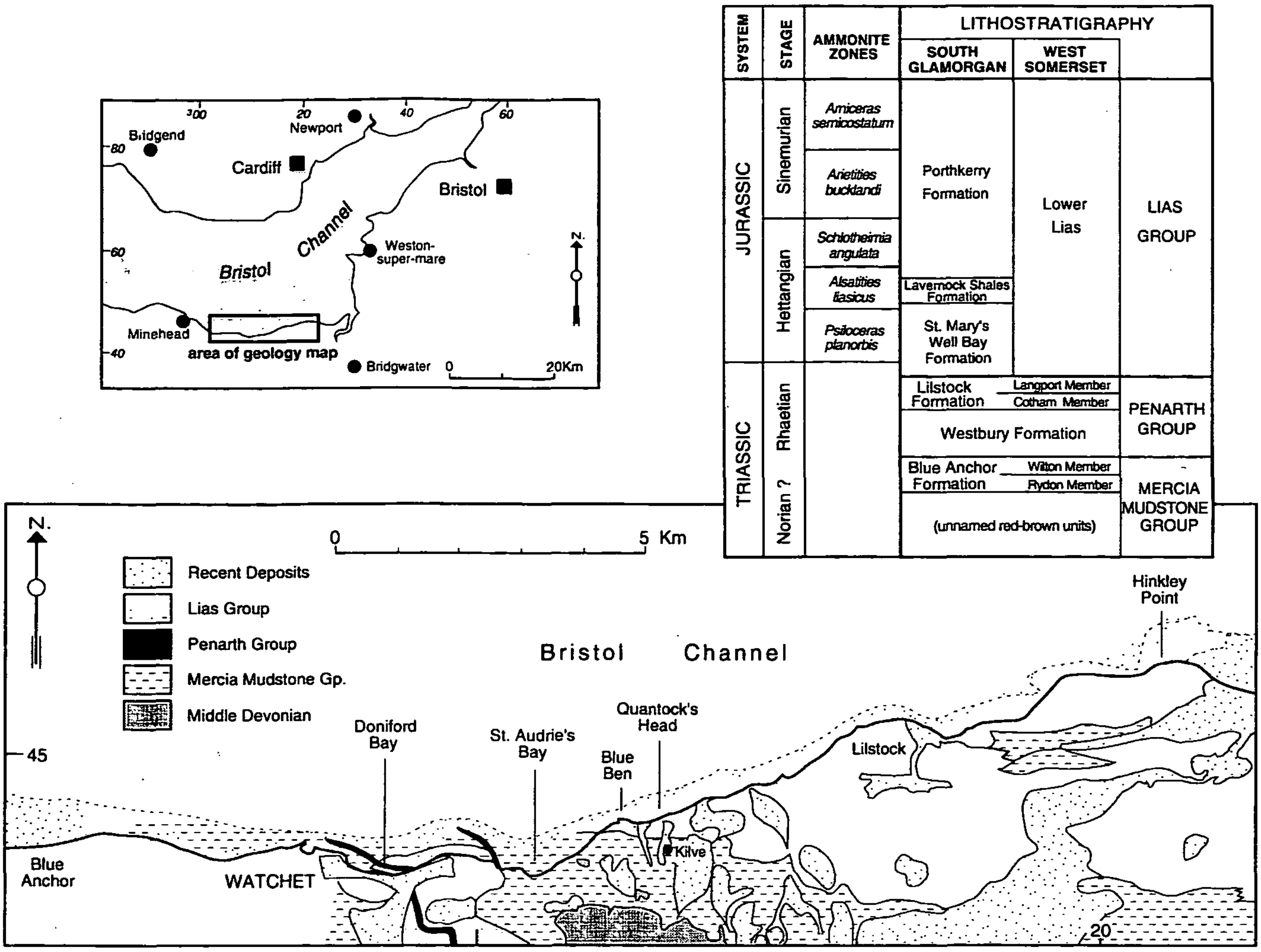

Figure 1. Location of the West Somerset succession and the position of Quantock's Head (lower map) within the Watchet to Lilstock SSSI. The position of the Hettangian/Sinemurian boundary is also located within the Lower Lias succession (top right). N.B. The village near the section is known as East Quantoxhead but the cliff on the coast is known as Quantock's Head.

SUBCLASS OSTRACODA Latreille, 1806
ORDER PODOCOPIDA Muller, 1894
Suborder Podocopina Sars, 1866
Superfamily Bairdiacea Sars, 1888
Family Bairdiidae Sars, 1888
Genus ***Bythocypris*** Brady, 1880
Type species: *Bythocypris reniformis* Brady, 1880

Bythocypris **sp.**
[not illustrated; see figures of Field, 1968]
cf. 1968 *Bythocypris sevenrockensis* Field, pp. 126-129, pl. 13, figs 1-15.

Diagnosis: A tumid species of *Bythocypris* with slightly angular posterior extremity occurring immediately below mid-height.

Material: Total 16 specimens.

Size: Average size of specimens:-

	Length	Height	Width
Right valve	0.68 mm	0.38 mm	
Left valve	0.68 mm	0.40 mm	0.30 mm (carapace)

Remarks: The specimens recorded here are very close to those described by Field (1968) as *Bythocypris sevenrockensis*. Unfortunately this species is only introduced in an unpublished thesis it can only be regarded as a manuscript name. The number, and quality, of the specimens found in this investigation preclude a formal determination of the new species. Initially described from the Angulata Zone of the Upper Hettangian on the Dorset Coast west of Lyme Regis this species has not been formally defined in the literature. A few specimens have been found in the uppermost Hettangian that may be referrable to this taxon, but without formal definition it is difficult to make direct comparisons. With a range from mid-Hettangian to Lower Sinemurian it may prove to be stratigraphically useful, although Field (1968) also reports it from the Lower Toarcian.

Stratigraphical Range: Field (1968) gives the 'normal' range as mid-Hettangian to Lower Sinemurian.

Superfamily Cypridacea Baird, 1845
Family Paracyprididae Sars, 1923
Genus ***Paracypris*** Sars, 1866
Type species: *Paracypris polita* Sars, 1866

Paracypris **sp. A.**
Figure 3.6
cf. 1968 *Paracypris? oertlii* Field, pp. 138-143, pl. 15, figs 6-10

Diagnosis: A relatively small species of *Paracypris* with a narrow rounded posterior extremity.

Material: Total 8 specimens.

Size: Average size of specimens:-

	Length	Height	Width
Left valve	0.40 mm	0.23 mm	0.18 mm

Remarks: This rare form is only tentatively compared to the species described by Field (1968). Unfortunately Field never published a full definition of the species, although material is reportedly held at University College, University of London.

Stratigraphical Range: Field (1968) gives the range of the species as mid-Hettangian to Upper Sinemurian.

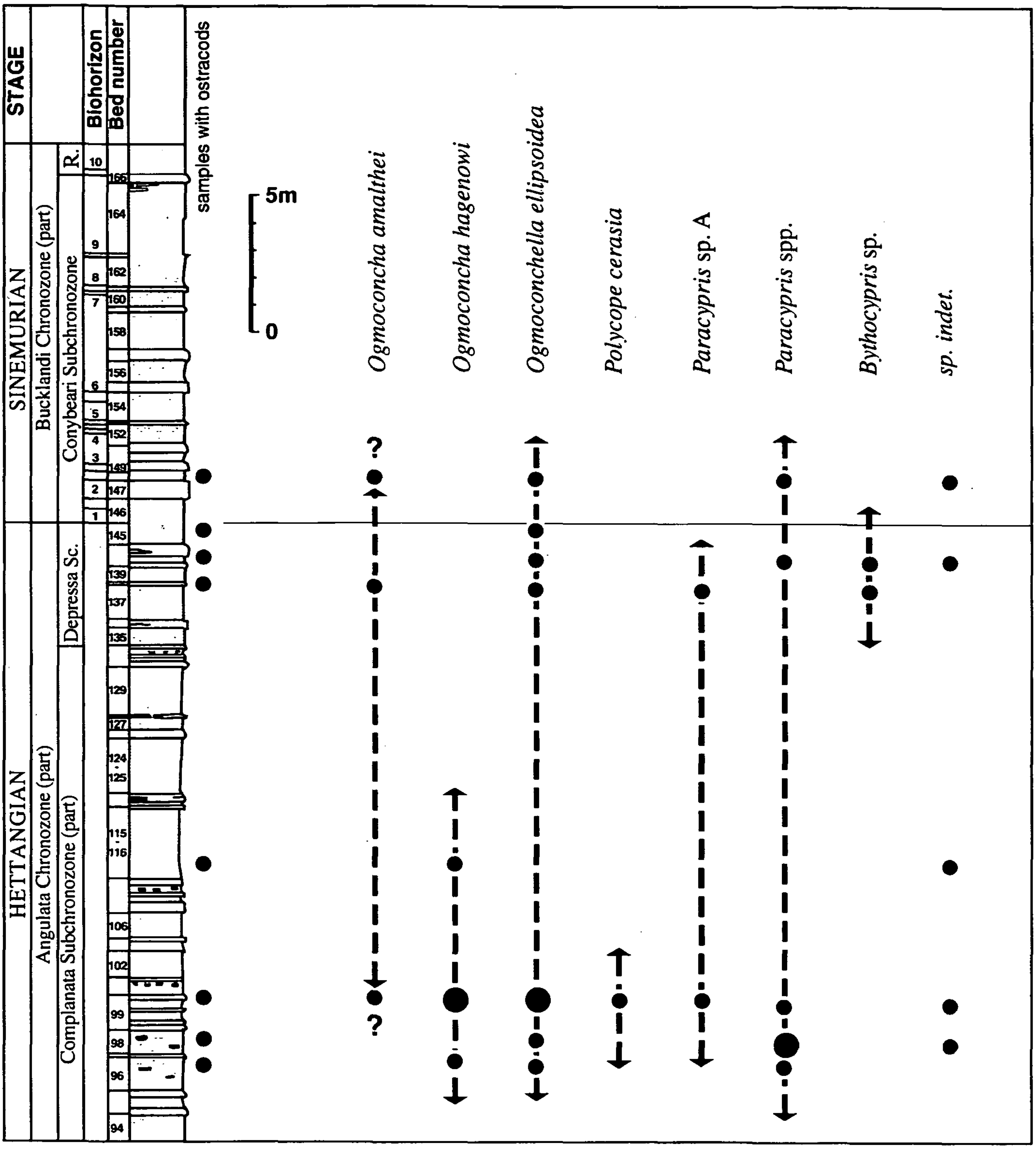

Figure 2. *The Hettangian/Sinemurian succession of the East Quantoxhead succession (after Page et al.,* in press*). Also indicated are the samples used in this investigation and the ranges of the ostracods reported in the text. Known extensions of ranges elsewhere in southern England are indicated by vertical (both upward and downward pointing) arrows. Large circles indicate >10 specimens; small circles indicate <10 specimens. Abbreviations on Figure: R = Rotiforme Subchronozone; Depressa Sc. = Depressa Subchronozone (not recognised by Field on the Dorset Coast).*

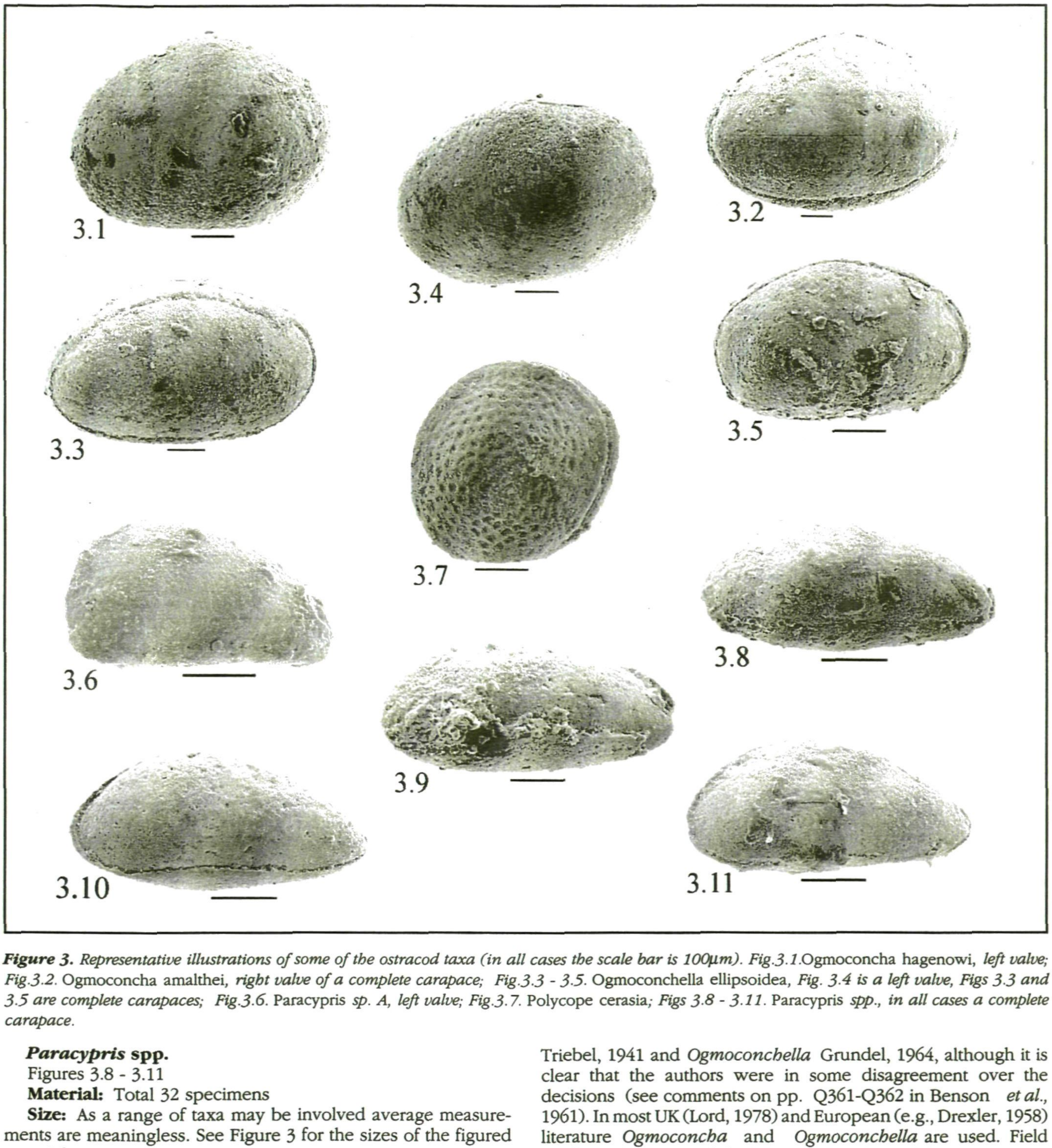

Figure 3. *Representative illustrations of some of the ostracod taxa (in all cases the scale bar is 100µm). Fig.3.1.*Ogmoconcha hagenowi, *left valve; Fig.3.2.* Ogmoconcha amalthei, ***right** valve of a complete carapace; Fig.3.3 - 3.5.* Ogmoconchella ellipsoidea, *Fig. 3.4 is a left valve, Figs 3.3 and 3.5 are complete carapaces; Fig.3.6.* Paracypris *sp. A, left valve; Fig.3.7.* Polycope cerasia*; Figs 3.8 - 3.11.* Paracypris *spp., in all cases a complete carapace.*

***Paracypris* spp.**
Figures 3.8 - 3.11
Material: Total 32 specimens

Size: As a range of taxa may be involved average measurements are meaningless. See Figure 3 for the sizes of the figured material.

Remarks: A number of paracyprid-like ostracods have been recorded in the samples from West Somerset, some of which may belong in *P.redcarensis* (Blake, 1876). Donze (1985) records only one species of *Paracypris* (again in open nomenclature) from the Pliensbachian of France. That species is unlike any of the indivduals recorded from the Somerset succession.

Suborder Metacopina Sylvester-Bradley, 1961
Superfamily Healdiacea Harlton, 1933
Family Healdiiidae Harlton, 1933

This long-ranging (Devonian to Lower Cretaceous) group of ostracods contains a number of relatively simple taxa in which the left valve is larger than the right valve and usually overlaps it around much of the margin. In the Treatise (Benson *et al.*, 1961) *Hungarella* Mehes, 1911 was given priority over *Ogmoconcha* Triebel, 1941 and *Ogmoconchella* Grundel, 1964, although it is clear that the authors were in some disagreement over the decisions (see comments on pp. Q361-Q362 in Benson *et al.*, 1961). In most UK (Lord, 1978) and European (e.g., Drexler, 1958) literature *Ogmoconcha* and *Ogmoconchella* are used. Field (1968), in his thesis, did adhere to the ruling of the Treatise and used *Hungarella* for these Liassic taxa. The differences are based, largely, on the muscle scar patterns but as these are rarely visible in Liassic material (including the samples from West Somerset) we cannot make any contribution to this debate.

Within this group of taxa there is considerable variation both within and between samples. There is also progressive morphological variation throughout the stratigraphical range of some of the defined taxa and, as a result, there is considerable difficulty involved in a consistent definition of the taxa. A fuller taxonomic investigation of the group is probably required using more material than we have at our disposal. Field (1968) has provided the most detailed analysis to date, but this remains unpublished.

In the absence of data on muscle scars we have attempted to distill the range of morphological variation into a consideration of:-

- the location of maximum height;
- overall shape (triangular to sub-rounded);
- the width/height proportions; and
- other distinctive features (e.g., distinct point in margin of left valve in *O. sinuosa* Drexler).

Figure 4 illustrates this range of features and identifies the species that we have recognised in the East Quantoxhead succession. *O. sinuosa* is also included for comparison.

Genus **Ogmoconcha** Triebel, 1941

Type Species: *Ogmoconcha amalthei* (Quenstedt, 1858)

Ogmoconcha amalthei (Quenstedt, 1858)

Figure 3.2.

1858 *Cypris amalthei* Quenstedt, pp. 164, 200, pl. 24, fig. 37a.

1950 *Ogmoconcha amalthei* (Quentstedt): Triebel, p. 118, pl. 1, figs 1-5, pl. 2, figs 13-17.

1968 *Hungarella amalthei* (Quenstedt): Field, pp. 83-84, pl. 6, figs 1-5.

1969 *Hungarella amalthei* (Quenstedt): Clark, pp. 100-102, pl. 2, figs 1-9.

Diagnosis: A moderately large species of *Ogmoconcha* with slightly inflated valves that have their greatest height approximately two-fifths valve length from the anterior.

Material: Total 20 specimens.

Size: Average size of specimens:-

	Length	Height	Width
Left valve	0.75 mm	0.52 mm	0.40 mm (carapace)
Right valve	0.70 mm	0.45 mm	

Remarks: *O. amalthei* is similar to *O. hagenowi* but the latter species is less elongate and more clearly inflated when viewed from the dorsal or ventral side. Field (1968) observed that these two species rarely occur together despite *O.hagenowi* being abundant in samples both above, and below, the range of *O.amalthei*.

Stratigraphical Range: This species has a restricted range (Field, 1968) in the lowest part of the Sinemurian. In our samples the species is also restricted to the uppermost Hettangian and the lowermost Sinemurian.

Ogmoconcha hagenowi Drexler, 1958

Figure 3.1.

1958 *Ogmoconcha hagenowi* Drexler, p. 58, pl. 21, figs 8a-f, pl. 26, figs 1-2.

1968 *Hungarella hagenowi* (Drexler): Field, pp. 93-95, pl. 6, figs 6-10, pl. 7, figs 1-7.

1969 *Hungarella hagenowi* (Drexler): Clark, pp. 102-105, pl. 3, figs 1-6, pl. 6, figs 3-4.

1978 *Ogmoconcha hagenowi* Drexler: Lord, p. 198, pl. 1, fig. 4, table 1.

1985 *Ogmoconcha hagenowi* Drexler: Donze, pl. 21, figs 14,15.

Diagnosis: A large species of *Ogmoconcha* that is sub-ovate in lateral view and with a valve apex at approximately mid-length. In some forms the left valve becomes almost triangular in appearance.

Material: Total 36 specimens.

Size: Average size of specimens:-

	Length	Height	Width
Right valve	0.68 mm	0.48 mm	
Left valve	0.70 mm	0.52 mm	0.40 mm (carapace)

Remarks: When Drexler erected this species in 1958 he also identified the sub-species *Ogmoconcha hagenowi sinuosa*. Field (1968) elevated this form to species level, recording it from the lower part of the Sinemurian on the Dorset Coast; horizons which in the Somerset successions are barren of ostracods. *Hungarella sinuosa* (Drexler) is characterised (Field, 1968, pp. 102-104) by a pointed posterior extremity at two-thirds valve height from the ventral margin (see Figure 4). This distinctive species has not been found in the Somerset material even though Field (1968) records a (usefully) limited range in part of the Lower Sinemurian.

Stratigraphical Range: The full range of this species (Field, 1968) is Lower Hettangian to mid-Sinemurian. In the West Somerset material it is common in the Upper Hettangian but was not found above the base of the Sinemurian. Donze (1985) gives an overall range for the taxon of mid-Hettangian to the Sinemurian/ Pliensbachian boundary.

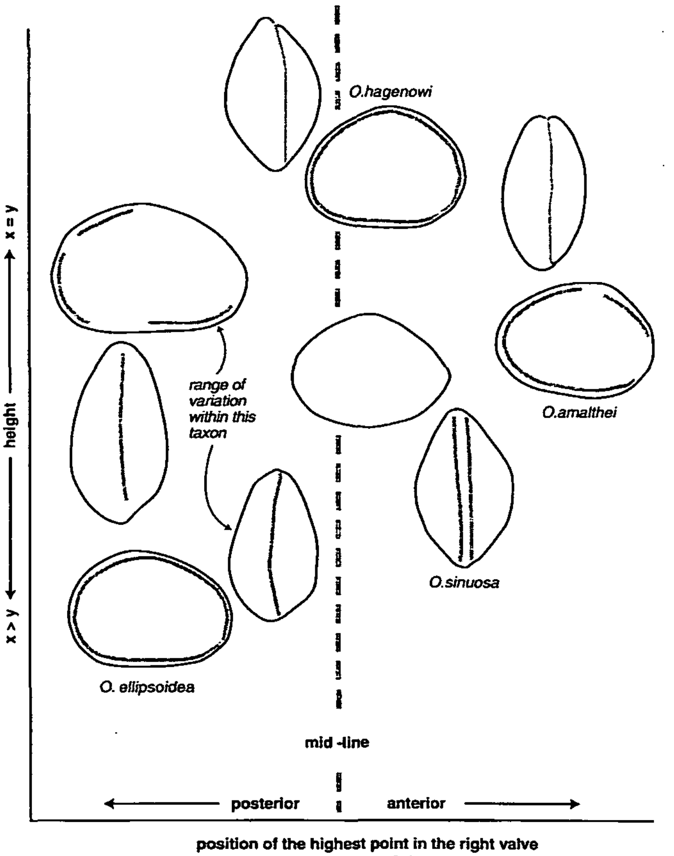

Figure 4. *Identification guide to species of the genus* Ogmoconcha *and* Ogmoconchella *recorded in the investigation. In each case the carapace is illustrated looking at the right valve or from the dorsal side. Taxa are located in approximate positions on a grid that shows the length:height ratio and the location of the maximum height in relation to the mid-point.* O. sinuosa *is included for reference.*

Genus **Ogmoconchella** Grundel, 1964

Type Species: *Healdia aspinata* Drexler, 1958

Ogmoconchella ellipsoidea (Jones, 1872)

Figures 3.3 to 3.5

1872 *Bairdia* (?) *ellipsoidea* G.S. Brady MS, Jones, p.146.

1876 *Bairdia liassica* Blake, in Tate and Blake, p. 430, pl. 12, fig. 1,1a.

?1958 *Healdia aspinata* Drexler, pp. 505,506, pl. 21, fig. 5a-e, pl. 25, figs 1-4.

?1964 *Hungarella owthorpensis* Anderson, pp. 147,148, pl. 14, figs 96-101.

?1964 *Ogmoconchella aspinata* (Drexler): Gründel, pp. 470,477, figs 5-7.

1968 *Hungarella liassica* (Blake): Field, pp. 95-102, pl. 10, figs 1-17, t.figs 15b, 16, 17.

1971 *Ogmoconcha ellipsoidea* (Jones): Lord, pp. 658-661, pl. 123, figs 9-13.

1978 *Ogmoconchella ellipsoidea* (Jones): Lord, p. 198, pl. 1, figs 1-3, table 1.

1985 *Ogmoconchella aspinata* (Drexler): Donze, pl. 21, fig. 10.

Diagnosis: A species of *Ogmoconchella* with an oval, inflated, carapace with greatest height posterior of mid-length.

Material: Total 62 specimens.

Size: Average size of specimens:-

	Length	Height	Width
Right valve	0.60 mm	0.37 mm	
Left valve	0.62 mm	0.40 mm	0.32 mm (carapace)

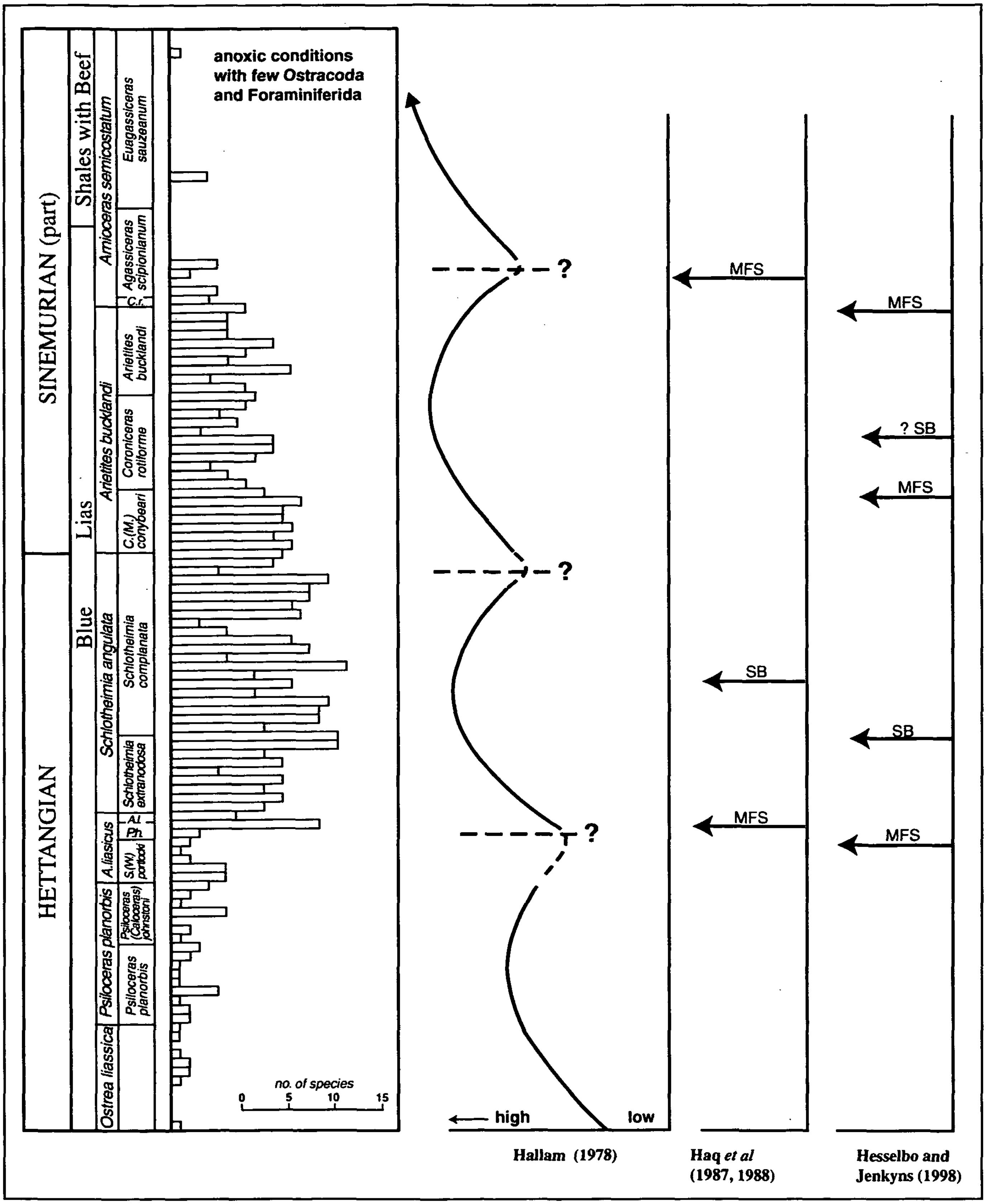

Figure 5. *Species diversity of the Lower Lias ostracods (after Field, 1968) plotted against the sea-level curve of Hallam (1978) and the sequence stratigraphy of Haq* et al. *(1987, 1988) and Hesselbo and Jenkyns (1998). Abbreviations: SB = Sequence Boundary; MFS = Maximum Flooding Surface. The Blue Lias and the Shales-with-Beef are the lowest lithological units of the Lias Group.*

Remarks: Lord (1971) has presented a full discussion of the taxonomic problems posed by the early definition of this taxon and *Bairdia liassica* Blake (1876). The name *Bairdia liassica* actually owes its origins to Brodie (1845, p. 80) who used it first as '*Cypris liassica*', but as there was never any proper definition or illustraion of the species given it should be regarded as invalid (Anderson, 1964, p. 133; Lord, 1971, pp. 659-660). Subsequently Blake (1876, p. 430) suppressed *Bairdia ellipsoidea* Jones (1872) in favour of *B. liassica*. This taxonomic problem is even more complicated, and Lord (1971) has attempted to provide a solution. Prior to his publication both Field (1968) and Clark (1969) used *liassica,* with the latter (Clark, 1969, fig. 27) illustrating a range of morphotypes that should be included within the definition of the species. In Figure 4 we have illustrated two extremes; one which accords with Blake's view (supported by Field and Clark) of the *liassica* 'morphotype', the other following Lord's (1971, 1978) view of *O. ellipsoidea*. There are slight differences, but as Clark (1969, fig. 27) has shown, the two forms in the Liassic material of the UK can be taken as a complete morphological spectrum. The full taxonomy of this taxon has not been investigated although most authors now regard *O. aspinata* as synonymous.

Stratigraphical Range: The range given by Lord (1978) is Hettangian to Lower Sinemurian while Donze (1985) gives *O. aspinata* an identical range.

ORDER MYODOCOPIDA Sars, 1866
Suborder Cladocopina Sars, 1866
Family Polycopidae Sars, 1866.
Genus ***Polycope*** Sars, 1866
Type species *Polycope orbicularis* Sars 1866

Polycope cerasia Blake, 1876
Figure 3.7
1876 *Polycope cerasia* Blake, p. 434, pl. 17, fig. 16.
1958 *Polycope cerasia* Blake: Drexler, p. 501, pl. 21, fig. 1.
1968 *Polycope cerasia* Blake: Field, pp. 47-49, pl. 1, figs 1-4.
1969 *Polycope cerasia* Blake: Clark, p. 83, pl. 1, figs 1-2.
1971 *Polycope cerasia* Blake: Lord, p. 645, pl. 122, figs 1,2.
1978 *Polycope cerasia* Blake: Lord, p. 204, pl. 4, figs 11-12, table 2.

Diagnosis: A small species of *Polycope* that is characterised by the presence of a valve margin that is accentuated by a smooth raised rib and a valve wall ornamented by shallow pitting.
Material: Total 3 specimens.
Size: Maximum dimension (average) 0.38 mm.

Remarks: Only a few specimens of this delicate taxon have been recovered in our samples. As delicate foraminifera (see Hylton, 1998) have been recorded from the same samples its low abundance is not thought to have been primarily caused by a too destructive processing technique.

Stratigraphical Range: Field (1968) records a range of mid-Hettangian to mid-Pleinsbachian, although Lord (1978) records a European range that extends to the mid-Toarcian.

SUMMARY

The ranges of the identified taxa are shown in Figure 2. In many cases the species recorded here are in the middle of their known ranges and, as such, their distribution in this succession does not assist in the definition of the base of the Sinemurian. It is, however, important that the fauna is described as a part of the work towards the proposal of the succession as the base Sinemurian GSSP. Two species, *O. amalthei* and *O. sinuosa,* have restricted ranges at, or about, the Hettangian/Sinemurian boundary. Before either can be proposed as distinctive enough for the micropalaeontological recognition of the boundary there would have to be further work on their distribution in both the East Quantoxhead succession and that on the Dorset Coast near Lyme Regis (the section described by Field, 1968). It is clear from this limited study that further work needs to be done on the distribution of the Ostracoda in the Liassic.

O. sinuosa is not recorded in our material but Field (1968) records it in samples from the lowest Sinemurian on the Dorset Coast. As our samples above the boundary are generally barren of ostracods we have been unable to confirm this distribution. *O. amalthei* is recorded by Field (1968) in the very uppermost Hettangian and the lowermost Sinemurian and this distribution is also reported from the Somerset Coast.

This absence of ostracods in the higher levels of the Sinemurian succession on the Dorset Coast is clearly shown by Field (1968) who plotted the species diversity throughout the succession. From low diversity faunas in the Lower Hettangian the fauna increases (see Figure 5) to a maximum of ca. 19 in the uppermost Hettangian (Complanata Sub-zone). Above that level the diversity decreases progressively until the fauna all but disappears in the uppermost part of the Blue Lias. In the West Somerset material (Figure 2) we record a diversity of ca. 7 - 9 (depending how many species of *Paracypris* are present), which is significantly less than in Dorset. The succession is more complete in Somerset and this may indicate deeper water conditions in that area. The loss of the ostracod and foraminiferal fauna up the succession above the boundary is also different to that recorded on the Dorset Coast (Lord *et al*., 1987) and, again, this may be due to differences in depositional environment between the two areas. Figure 5 also shows how the distribution of the ostracod faunas relate to the changes in sea-level proposed by Hallam (1978) and the sequence boundaries and maximum flooding surfaces suggested by Haq *et al.* (1987, 1988). In a recently published review of Lower Jurassic sequence stratigraphy, Hesselbo and Jenkyns (1998) have indicated - on a general scale - the sequence boundaries and maximum flooding events, together with a generalised sea-level curve. There is considerable variation in the placing of these 'events', and few (if any) appear to equate with the ostracod diversity changes. The basinwide flooding event (key surface) of Hesselbo and Jenkyns (1998, fig.11) at the Bucklandi - Semicostatum Sub-zone boundary is close to the disappearance of the fauna shown in Figure 5 and this might imply that the deeper, anoxic, water is the cause of the restriction on the ostracod assemblage. The marked diversification of the ostracod fauna in the upper part of the Liasicus Sub-Zone might be close to the tentative flooding event of Hesselbo and Jenkyns but that is by no means clear.

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East Quantoxhead, Somerset: a Candidate Global Stratotype Section and Point for the Base of the Sinemurian Stage (Lower Jurassic)

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Abstract: The base of the Sinemurian Stage is drawn at the base of the Conybeari Subzone of the Bucklandi Chronozone, the type area of which includes Dorset and Somerset, south-west England. Recent study of extensive coastal sections in West Somerset has revealed one of the most expanded fossiliferous sequences across this boundary known in Europe - the Conybeari Subchronozone alone reaching nearly 13m in thickness. Excellent cliff and foreshore exposures in 'Blue Lias' facies Lower Lias north of East Quantoxhead are eminently suitable as a reference section, and here the Hettangian/Sinemurian boundary is drawn at a level 0.75m below the top of British Geological Survey Bed 146. The terminal Hettangian (Depressa Subchronozone, Angulata Chronozone) is indicated by *Schlotheimia* ex gr. *princeps* S. Buckman and *S. pseudomoreana* Spath and the base of the Sinemurian (Conybeari Subchronozone, Bucklandi chronozone) is characterised by abundant crushed *Vermiceras quantoxense* n. sp. Higher levels in the Conybeari Subchronozone yield species of *Metophioceras*, *Vermiceras*, *V. (Epammonites)*, early *Coroniceras* and schlotheimiids of the *charmassei* group. These exposures have now been subjected to multidisciplinary stratigraphic analysis in order to establish a range of correlation methods, as is recommended by ICS guidelines. The boundary is now also correlatable using calcareous foraminifera and Gamma-ray logs (at least regionally) and potentially using ostracods. Palynological results are presently poor, however, and remagnetisation makes the section unsuitable for magnetostratigraphical correlation. Although primarily established on the basis of the change in ammonite faunas, the combined multidisciplinary results indicate that the Hettangian/Sinemurian boundary at East Quantoxhead is a viable candidate GSSP and the site is here so proposed.

Introduction

The Sinemurian Stage was proposed by Alcide d'Orbigny in 1842, as the lowest division of the Jurassic System and was named after the town of Semur-en-Auxois, in northern Burgundy (eastern France), where canal construction and other excavations had yielded many characteristic fossils, especially ammonites. The establishment of the Hettangian Stage by Renevier (1864) for the basal part of d'Orbigny's Sinemurian, restricted the latter as the second stage of a conventional Jurassic System (Arkell, 1933).

The basic framework of correlative zones for the Sinemurian Stage was originally established by Oppel (1856) and subsequent refinement led to the standard scheme of Donovan in Dean et al. (1961). The base of the stage is drawn at the base of the lowest subchronozone of the lowest zone, namely the Conybeari Subchronozone of the Bucklandi Chronozone, the type area of which is south-west England, including Somerset (Tutcher, 1918). Donovan in Morton (1971) proposed that sections near Lyme Regis, on the Dorset coast (Page, 1995, fig. 1), described by Lang (1924) should be established as a stratotype for the Sinemurian Stage (although Sinemurian-type faunas have now been recorded slightly lower: Palmer, 1972a; 1972b; Page, 1992, p. 136).

Recent study of coastal sections in West Somerset (Fig. 1), described by Palmer (1972a) and Whittaker and Green (1983- including a brief review of the ammonite faunas by Ivimey-Cook and Donovan), has revealed a considerably expanded Hettangian/Sinemurian boundary sequence nearly five times thicker than at Lyme Regis. The sequence is exposed near East Quantoxhead, east of

Watchet, at a site referred to by Palmer as "Limekiln Steps". In addition it has been possible to demonstrate that the earliest Sinemurian-type fauna at Lyme Regis is preceded by another, earlier fauna near East Quantoxhead (Page, 1992, p. 136). The Dorset section is therefore not considered to be a suitable stratotype for the base of the Sinemurian, whereas the Somerset succession has great potential.

The combination of a good faunal sucession and expanded sequence (ca.13m for the Conybeari Subchronozone alone) makes the locality unusual in Europe. Elsewhere, for instance near Bristol (e.g., Saltford Cutting; Donovan, 1952a; 1952b; 1956; Donovan and Kellaway, 1984), southern Germany (Bloos, 1985 a; 1985b) and south-east France (Corna, 1985; 1987; Elmi and Mouterde, 1965), sequences are usually much thinner and much less complete even at the historical "type" locality for the Stage near Semur-en-Auxois itself (Corna and Mouterde, 1988). Only in Glamorgan (S. Wales) is the subchronozone known to be thicker (Trueman 1922; 1930; Wilson et al., 1990; pers. obs. 1994), but the faunal sequence seems to be poorer, especially in the region of the Hettangian/Sinemurian boundary.

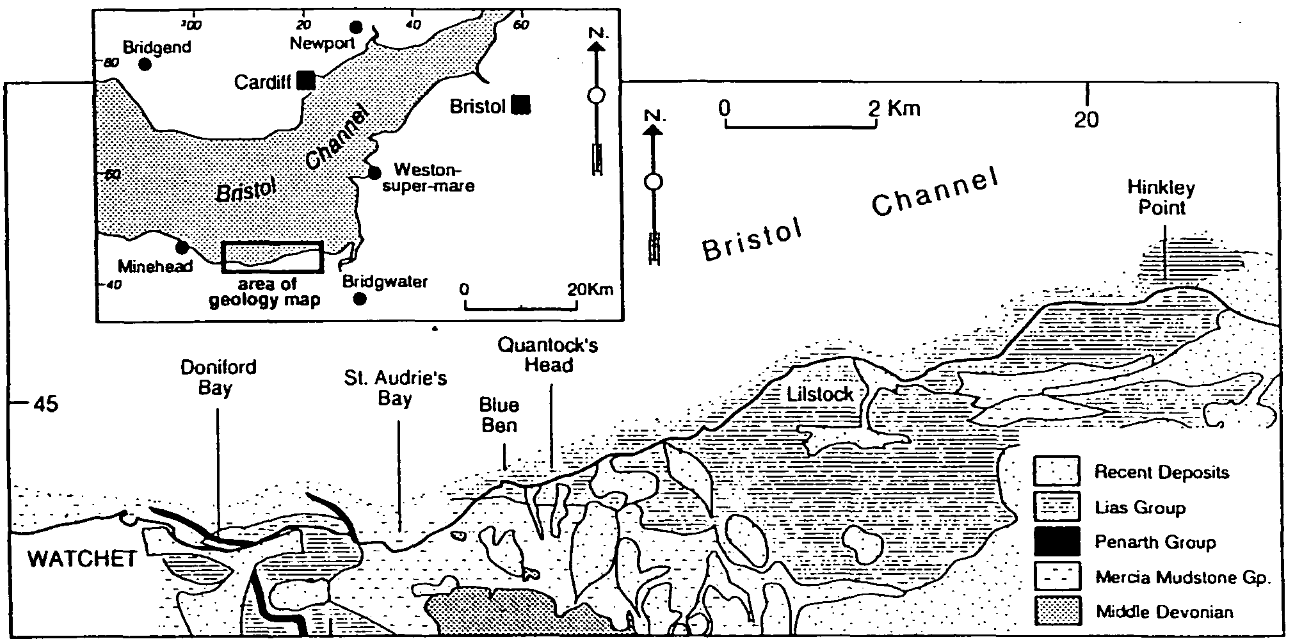

Figure 1: Location map and local geology of the Lower Jurassic (Hettangian-Sinemurian), coastal section at East Quantoxhead (after Warrington and Ivimey-Cook, 1995)

Stratigraphic Characteristics of the Boundary Interval

Ammonite Faunas and Standard Zonations (K.N.P., G.B.)

The faunal sequence in West Somerset is the most complete known in the North West European Province and can form a standard with which to correlate sequences elsewhere (Fig. 2). The sequence of faunas in the Early Sinemurian was characterised as a series of potentially correlatable infra-subzonal units or *biohorizons* (*sensu* Callomon, 1985; Page, 1992) by Page (1995). Further work by Bloos and Page (this volume) has recognised additional faunas in the Early Sinemurian and better characterised the Hettangian sequence below. The change from typically "Hettangian" to typically "Sinemurian" faunas is conventionally indicated by the virtual replacement of faunas dominated by *Schlotheimia* spp. (Schlotheimiidae) of the Angulata Chronozone (Upper Hettangian), by faunas dominated by Arietitinae (including *Vermiceras*, *V. (Epammonites)*, and *Metophioceras*) of the early Bucklandi Chronozone (Lower Sinemurian). The following is a summary of the succession across the boundary (for more details see Bloos and Page, this volume):

Hettangian: Angulata Chronozone, Complanata Subchronozone (>16m): Beds 95-133 (C52-C90) contain a typical fauna of the Complanata Subchronozone of Germany, including

Schlotheimia complanata Koenen, *S. oxygonia*, *S. tenuis*, *S. macilenta*, *S. polyeides*, *S. angulosa*, *S. oligoptycha* (all Lange, 1951) and *S.* ex gr. *striatissima* (Quenstedt).

Depressa Subchronozone (4.5m): *S. princeps* (Bayle) is a typical species of the subchronozone in south-west Germany and a similar form is present in Bed 134 (C 91). *S. pseudomoreana* (Spath) appears in Bed 135 and persists up to the top of the Hettangian in Bed 145 (C100, 60cm above limestone Bed 144) (includes the *pseudomoreana* and *Schlotheimia* sp. 2 biohorizons of Page, 1995).

Sinemurian: Bucklandi Chronozone, Conybeari Subchronozone (13m): The base of the Sinemurian is marked by the sudden appearance of *Vermiceras quantoxense* n. sp. (Bloos and Page, this volume), *V. palmeri* n. sp., *Metophioceras* sp. indet. A in Bed 146/145 (C100) with base at a level 0.75m below Bed 147 (*quantoxense* Biohorizon, = cf./aff. *rougemonti* Biohorizon of Page 1992; 1995).

Poorly characterised large *Metophioceras* sp. indet. B and schlotheimiids of the *charmassei* group are present in Bed 147 (C101) (*Metophioceras* sp. 1 Biohorizon of Page 1995). Bed 149 (C103) yields a good fauna including *M. brevidorsale* (Quenstedt), *V. spiratissimum* (Quenstedt), *V. rougemonti* (Reynès), *V. conybearoides* (Reynès), and schlotheimiids of the *charmassei* group (*conybearoides* Biohorizon, = *Metophioceras* sp. 2 Biohorizon of Page, 1995 and *longidomus* Biohorizon of Page, 1992). This fauna is often the lowermost recorded elsewhere in Britain (e.g., from around Bristol) and in Germany and France (Bloos and Page, this volume). Higher faunas in the subchronozone are broadly as characterised by Page (1995), but with the addition of an aff. *quantoxense* Biohorizon (Bed 158/C112), an *elegans* Biohorizon nov. (Bed 160/C114) and the *silvestrei* Biohorizon – the latter already known from Germany (Bed 163/C118) (Bloos and Page, this volume).

Foraminifera (M.H., M.B.H.)

Although planktonic foraminifera probably originated in the Late Triassic, benthic forms predominate during the Lower Jurassic and show very consistent stratigraphic ranges throughout NW Europe (Copestake, 1985; Copestake and Johnson, 1989). Benthic foraminifera are of great value in subdividing and correlating the Lower Jurassic with an obvious importance in situations where ammonites are not recovered.

Sampling: A total of 35 samples of shale and mudstone were taken from the section at East Quantoxhead with an emphasis placed on the boundary shale. Samples labelled EQH were provided by K.N.P. and those labelled QTX were collected by M.B.H. Around 200 grams of material was processed using standard disaggregation techniques and at least 300 individuals from each sample were picked, where possible, to obtain a representative assemblage of the species present (Dennison and Hay, 1967).

Results: The results of a preliminary study of the section at East Quantoxhead are summarized by Hylton (1998) and have now been augmented by additional results providing valuable data on the nature of the foraminiferal fauna across the Hettangian/Sinemurian boundary (Fig. 2). The predominance of calcareous foraminifera and especially the *Lingulina tenera* plexus group is typical of Lower Jurassic sequences in Northern Europe and the United Kingdom. The assemblages also comprise useful index species and other forms diagnostic of the Lower Jurassic and the Hettangian - Sinemurian in particular. The first and last appearances of *Lingulina tenera* plex. *substriata* are restricted to the top of the Hettangian Angulata Chronozone and are therefore useful for correlating the base of the Sinemurian (Copestake and Johnson, 1989). The consistent appearance of *Planularia inaequistriata* and the *Frondicularia terquemi* plexus group above the boundary at East Quantoxhead is a further characteristic to identify the base of the Sinemurian. Copestake and Johnson (1984) also include the important index species *Lingulina tenera* plex. *substriata*, *Planularia inaequistriata* and *Dentalina matutina* in their benthic foraminiferal zonation scheme. This scheme, of international applicability for both southern and northern hemispheres, covers Britain and seventeen other countries and regions throughout the world. The foraminiferal species discussed here are those considered to be the most important for zonation and correlation purposes in the British and Northwest European Lower Jurassic (Copestake and Johnson, 1989). Accordingly, this study has shown that the foraminifera from East Quantoxhead could provide a useful tool for correlation of the proposed GSSP with other sections.

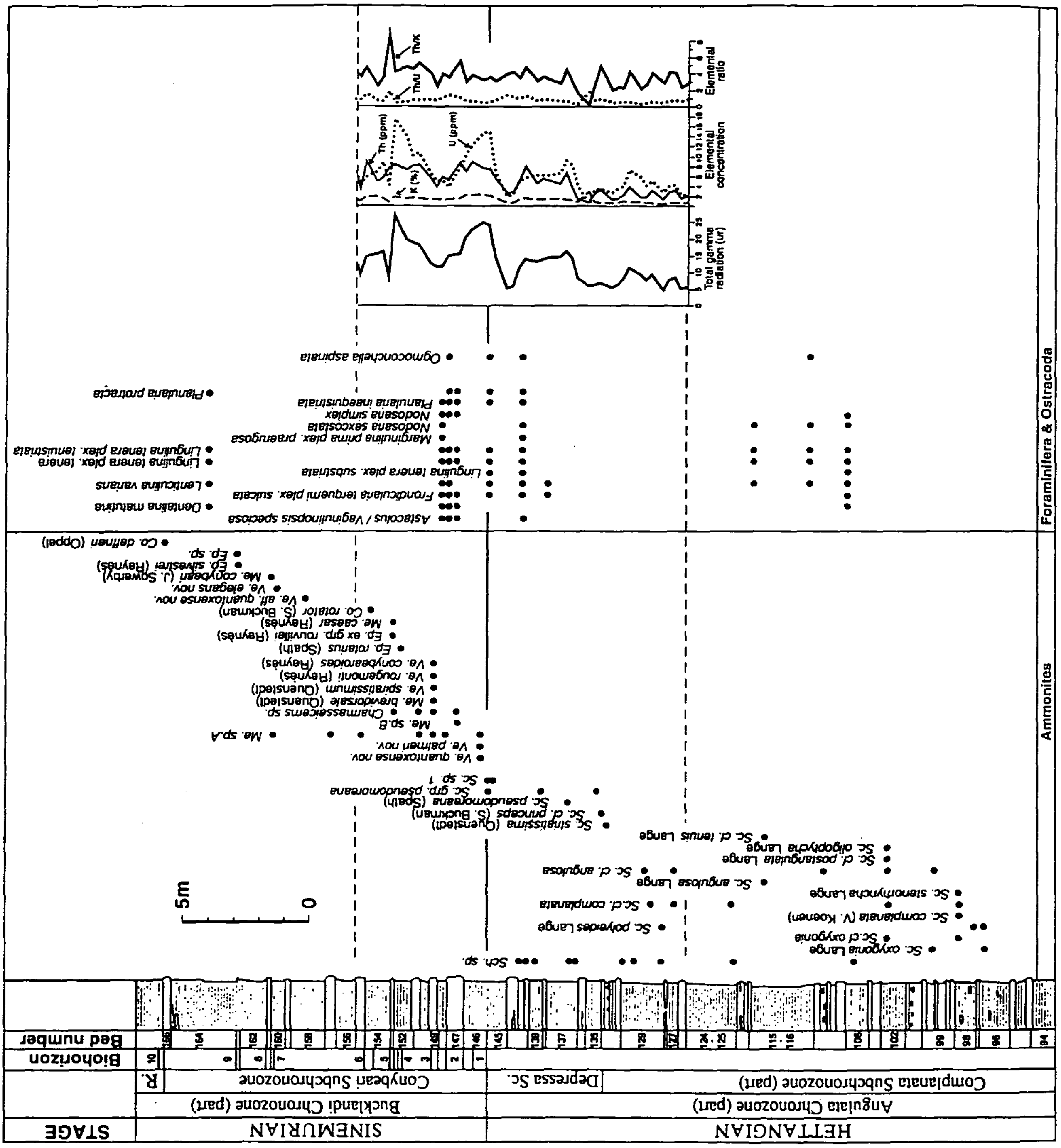

Figure 2. The Hettangian/Sinemurian boundary sequence near Limekiln Steps, East Quantoxhead: Stratigraphical synthesis (bed numbers are those of Whittaker and Green, 1983). Biohorizons numbered as follows: 1- *quantoxense*, 2- *Metophioceras* sp. B, 3- *conybearoides*, 4- *rotarius*, 5- *rouvillei*, 6- *rotator*, 7- *elegans*, 8- *conybeari*, 9- *silvestrei*, 10- *defneri*. (R.= Rotiforme Sunchronozone, *Sc.*= *Schlotheimia*, *Ve.*= *Vermiceras*, *Me.*= *Metophioceras*, *Ep.*= *Epammonites*, *Co.*= *Coroniceras*).

Ostracoda (M.H., M.B.H.)
Sampling: Processing and sample details were as for the foraminiferal study.
Results: Occurrences of ostracod carapaces or valves in the samples were sporadic. Five samples, however, yielded low numbers of specimens (from beds 148, 145, 141 and 114; Fig. 2), dominated by the healdiid genus *Ogmoconchella*, almost entirely as *O. aspinata* (Drexler) which is widespread in the European Hettangian (Lord, 1978). This form ranges from the Hettangian to Lower Sinemurian and is a useful index species for this part of the Lower Jurassic.

Palynology (M.F., M.B.H.)
Samples obtained to date indicate only poorly preserved assemblages (probably largely due to surface weathering), but with continued sampling it is believed that better assemblages will be recovered. No stratigraphic conclusions can therefore be made at this stage.

Magnetostratigraphy (D.E.R., A.M.)
Six beds across the boundary sequence were cored (four in limestone and two in shale). Samples were subjected to progressive alternating field (AF) demagnetisation. Remanences were measured using a JR4 Spinner Magnetometer. IRM acquisition experiments were conducted to determine the magnetic mineralogy.
Results: (i) AF demagnetisation easily removed all the natural remanent magnetism (NRM) of these samples (median destructive field = 10 mT). Clear, single components of magnetisation were isolated using principal component analysis. (ii) IRM experiments showed a rapid increase in isothermal moment with applied fields of up to 150-300 mT. This suggests that the NRM in these samples is carried by magnetite. The low median destructive fields suggest the presence of multi-domain magnetite. (iii) The mean remanence direction is:

In situ:	Dec=003°	Inc=71°	95=11.0°	K=70.4
Tilt corrected:	Dec=010°	Inc=65.6°	95=11.7°	K=62.5

Discussion: The results indicate that the *in situ* direction is in close alignment with the present day axial geocentric magnetic field at the site (Dec=0°, Inc=68°). Primary (Jurassic) remanences are thus expected to have inclinations of around 50°. These data therefore suggest that the section has been remagnetised in the present day direction. This is supported by the slight increase in dispersion after tilt correction (although this is not statistically significant).
Conclusion: The section has been remagnetised, possibly during recent weathering. Primary remanences are not recoverable, even with detailed progressive demagnetisation.

Gamma Ray (J.L.B., S.P.H., H.J.)
A spectral gamma-ray survey of the 'Blue Lias' sequence on the West Somerset coast and other Hettangian-Sinemurian sections in SW England, has recently been published in outline (Bessa and Hesselbo, 1997). Figure 2 shows a detailed survey across the Hettangian/Sinemurian boundary in West Somerset. Sample stations are at 0.3m intervals. Pattern matching of gamma-ray characteristics can be used to correlate outcrop to borehole, to a resolution that varies from about 0.5 to 3m (cf. discussion in Whittaker et al., 1985; Smith, 1989; Bessa and Hesselbo, 1997).

A particular characteristic of the boundary section is the occurrence of two marked peaks in U concentration, one just above the boundary and one some four metres above it. These are linked to the occurrence of dark organic-rich shales, which may themselves be of value when correlating lithostratigraphically within the basin. Correlation with other basins has not yet been attempted but the observations in West Somerset indicate that gamma-ray logs may have some potential for correlation of the Hettangian/Sinemurian boundary, at least regionally.

Satisfaction of ICS GSSP Criteria

The effective communication of the relationships in time and space between different rock bodies and events and processes during the evolution of the Earth requires an unambiguously defined chronostratigraphic nomenclature. *Global Stratotype Sections and Points* or GSSPs unambiguously and objectively define the boundaries between successive divisions of a chronostratigraphic scale at a chosen stratotype locality (Salvador, 1994). Remane et al. (1996) review the ideal requirements of a candidate GSSP, but accept that not all sections are likely to fulfil every requirement. These requirements are listed below with an assessment of the suitability of the Quantoxhead section:

"4.1 Geological Requirements"

(a) "Exposure over an adequate thickness": The large scale of the exposures at East Quantoxhead and the relative stratigraphic completeness (including the great thickness of the trans-boundary sequence) make the section ideal as a candidate GSSP. The boundary interval is exposed and accessible for over 200m along the cliff and foreshore. The section forms part of a continuous stratigraphic sequence from Norian (Upper Triassic) to Semicostatum Chronozone, Lyra Subchronozone (middle Lower Sinemurian).

(b) "Continuous sedimentation": The relative expansion of the boundary sequence when compared to other localities in the region (e.g. 13m for the Conybeari Subzchronozone alone, as opposed to about 5.4m near Lyme Regis on the Devon/Dorset coast), the presence of faunas not known from elsewhere and the lack of any sedimentological indication of condensation or non-sequence near the boundary level, suggests that virtually continuous sedimentation characterises the Quantoxhead succession.

(c) "The rate of sedimentation": The relative thickness of the boundary sequence and the position of the boundary within a major mudrock unit indicate a high rate of sedimentation. The presence of ammonite faunas not known from elsewhere indicates that successive events can be adequately distinguished.

(d) "Absence of synsedimentary and tectonic disturbances": There are no significant synsedimentary disturbances in the boundary sequence. Although the Liassic sequence of the region is incorporated onto a tectonic inversion (Dart et al., 1995), faulting in the area of the proposed GSSP does not significantly disrupt the boundary sequence which lies entirely within a single faulted wedge.

(e) "Absence of metamorphism and strong diagenetic alteration": The area is free from metamorphism and significant diagenetic alteration.

"4.2 Biostratigraphic Requirements"

(f) "Abundance and diversity of well-preserved fossils": Ammonite faunas are abundant at many levels across the boundary sequence. Preservation is often good, with solid specimens in limestones and crushed (but determinable) shells in mudrocks. No other stratigraphically diagnostic macrofossils are present. Microfaunas include foraminifera and ostracods, the former in particular yielding results of taxonomic importance. Palynological information is presently incomplete but may benefit from future sampling of additional levels.

(g) "Absence of vertical facies changes": The boundary interval lies within a thick sequence of alternating mudrocks (bituminous shale, non-bituminous marl) and bedded or nodular limestone. The boundary itself is placed *within* a single bituminous mudrock unit. There is therefore no significant change of litho- or biofacies across the boundary.

(h) "Favourable facies for long-range biostratigraphic correlation": The succession was laid down in an open-marine environment and most of the taxa present are known to have a wide geographical range (for the ammonites, many species are recorded throughout the Northwest European Province and some also in the Tethyan Province).

"4.3 Other Methods"

(i) "Radioisotopic dating": The technique has not been attempted.

(j) "Magnetostratigraphy": The section has been remagnetised and primary remanences have not been recovered, even with detailed progressive demagnetisation. The section is not therefore suitable for magnetostratigraphical correlation.

(k) "Chemostratigraphy": The section offers a good potential for such studies, including strontium isotope analysis.

(l) "Regional paleogeographical context" and "facies relationships": The area lies within the Northwest European Province with free marine connection during the Hettangian and Sinemurian to the rest of Europe and Asia. The widespread occurrence of comparable limestone-mudrock alternations throughout the region suggests that facies variations are unlikely to affect the distribution of faunas and floras of correlative importance.

"4.4 Other Requirements"

(m) "Permanently fixed marker": A marker could be placed, with landowner's permission, adjacent to the exposure at the top of the cliff. Any marking of the cliff itself is likely to be temporary due to active coastal erosion (unless attached directly to Limekiln Steps).

(n) "Accessibility": The site is freely accessible along public rights of way and on open coastal foreshore. Steps down to the beach at grid ref: ST137443 ("Limekiln Steps") descend over the boundary interval - these steps are linked to car parking at Kilve and East Quantoxhead, both around 900m from the proposed GSSP. The site is also accessible along the beach from Kilve when tides are low. Visiting on a falling tide is recommended.

(o) "Free access": Public access along rights of way (footpaths) and along the foreshore is guaranteed under English law.

(p) "Guarantees from the respective authority concerning free access for research and permanent protection of the site": The site is protected under national conservation law (Wildlife and Countryside Act 1981) and lies within the legally designated Blue Anchor to Lilstock Coast Site of Special Scientific Interest (Page et al., 1994). Advice concerning protocols for sampling programs and other enquiries should be directed to English Nature at Roughmoor, Bishops Hull, Taunton, Somerset, TA1 5AA, U.K.

Conclusions

Results to date indicate that the section at East Quantoxhead demonstrates the most complete known Hettangian/Sinemurian boundary succession. The sequence of ammonite faunas is unrivalled and therefore has great potential for detailed international correlations. Foraminifera also facilitate correlation of the boundary and ostracods, although presently incompletely known, may ultimately yield useful results. Gamma ray log correlation is possible, at least regionally, whereas for magnetostratigraphic results, an additional supporting section may be required. When combined with the excellent quality of the exposures and their high level of permanence and protection, the cliffs and foreshore become an ideal candidate Global Stratotype Section and Point for the base of Sinemurian Stage of the Jurassic System.

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Benthic Foraminiferal Response to Pliensbachian - Toarcian (Lower Jurassic) Sea-Level Change and Oceanic Anoxia in NW Europe

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Abstract: The Early Jurassic was a time of rapidly rising sea level associated with the extensive spread of anoxic bottom waters. Sea-level rise across the Pliensbachian - Toarcian boundary culminated in the *falciferum* zone of the Toarcian and is one of the best authenticated eustatic events in the Jurassic. This major transgressive pulse was marked by deeper water marine sequences and was associated with the deposition of organic-rich shales.

The development of anoxia coincides with a notable period of mass extinction of the marine fauna. High resolution sampling and study of the microfaunas through several sequences in the United Kingdom confirm that benthic foraminiferal faunas were similarly affected by an Early Toarcian falciferum zone event. Samples were analysed from Pliensbachian - Toarcian mudstone, clay and shale sequences of the South Dorset Coast, the Midlands and the Yorkshire Coast. The sections studied show distinct changes in assemblages across the Pliensbachian - Toarcian boundary and in the basal zones of the Toarcian.

Evidence for a foraminiferal extinction event in the Pliensbachian - Toarcian includes the elimination of the important Lower Jurassic *Lingulina tenera*, *Frondicularia terquemi* and *Marginulina prima* plexus groups, initiating a significant period of turnover of the microfauna. A marked change also occurred in the character of associated nodosariid assemblages: the uniserial forms of *Nodosaria*, *Frondicularia* and *Lingulina*, dominating the Pliensbachian assemblages, were largely replaced by coiled *Lenticulina* in the Early Toarcian. A reduction in test size and a decline in species diversity, compared with Hettangian to Sinemurian foraminiferal assemblages, reflect the development of low oxygen conditions followed by a subsequent renewal of the microfauna in the Middle Toarcian.

The foraminiferal data from the UK sections we have studied correlates with microfaunal responses reported from NW European Pliensbachian - Toarcian black shale sequences in SW Germany.

Introduction

Through their analysis of extinction periodicity, based on family-level data of marine extinctions, Raup and Sepkoski (1984; 1986) and Sepkoski and Raup (1986) claim to have recognised two events in the Jurassic, one of which was placed at the end of the Pliensbachian. This analysis, however, was at the stage level of resolution and the event was later reassessed as probably taking place in the Lower Toarcian, based on the recognition of a clear-cut extinction in Western Europe (Hallam, 1986; 1987).

Sea-level rise across the Pliensbachian - Toarcian boundary culminates in the *falciferum* zone of the Toarcian and is one of the best authenticated eustatic events in the Jurassic (Hallam, 1997). This major transgressive pulse is marked by apparent deepening in marine sequences in extensive parts of the world (Hallam, 1988) and is associated with widespread deposition of organic-rich shales. Jenkyns (1988) recognised that this period corresponds with high rates of carbon burial and a sharp positive excursion in the carbon isotope curve, signifying the Early Toarcian oceanic anoxic event.

This anoxic event coincided with a notable period of mass extinction of marine faunas. Sampling of invertebrate macrofauna through complete expanded sequences in NW Europe has shown that most species extinctions occurred in the Early Toarcian following a regional anoxic event (Little and Benton, 1995). The extinction event first recognised by Hallam (1961), led to an almost complete species turnover among the benthos in the *falciferum* zone.

Background to Early Jurassic Extinction Events

The most complete Lower Jurassic sequence studied for foraminifera in the U.K. was cored in the Llanbedr (Mochras Farm) borehole, north Wales, between 1966 and 1969 (Woodland, 1971). Johnson (1975) studied the foraminifera of the Upper Pliensbachian and Toarcian with the Hettangian to Lower Pliensbachian section being completed by Copestake (1978). These two works, although remaining largely unpublished, contain a considerable amount of information. Data relevant to this study (*margaritatus* to *variabilis* zones) has been re-examined and summarised in Figure 1.

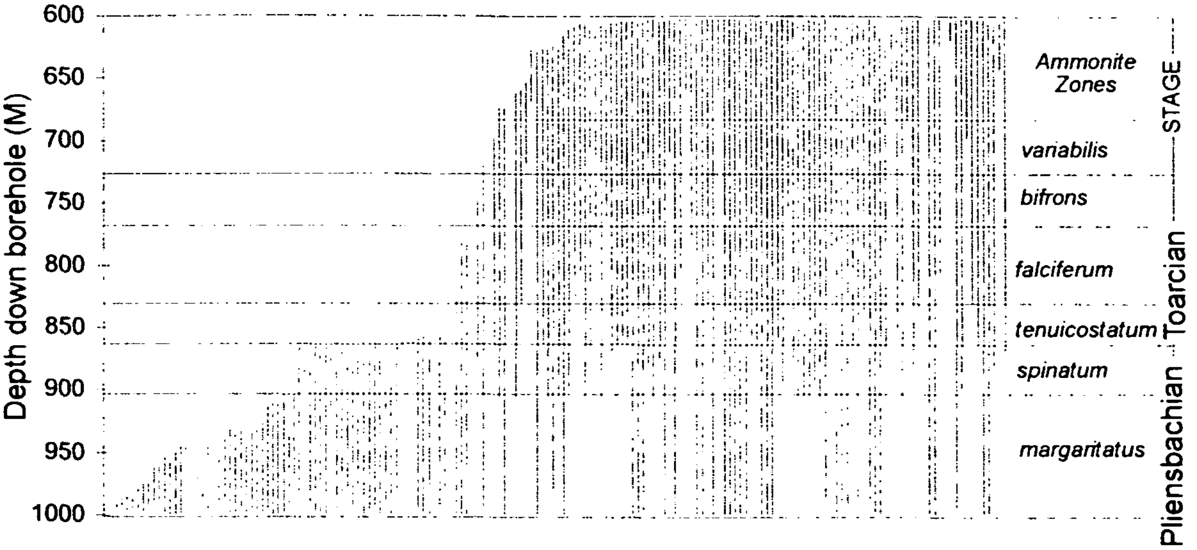


Figure 1. Benthic foraminiferal ranges from the Mochras Borehole, Wales, UK. Ranges compiled from Johnson (1975) and Copestake (1978).

The Mochras borehole foraminiferal fauna in Fig. 1 shows distinct changes in assemblages across the Pliensbachian - Toarcian boundary and during the basal zone of the Toarcian. During the *tenuicostatum* zone foraminifera show a decrease in diversity, as ecological stress developed and continued throughout the zone (Johnson, 1975). Deepening resulted in a reduction in bottom water circulation and this trend reached its acme in the basal *exaratum* subzone of the succeeding *falciferum* zone. The subsequent stratigraphic record of normal marine conditions is here absent due to faulting, although the missing section is entirely within the *exaratum* subzone (Johnson, 1975).

Brasier (1988) noted that while there is little available evidence for foraminiferal mass extinction events in the Lower Jurassic, certain groups were eliminated in boreal regions including the important Lower Jurassic *Lingulina tenera, Frondicularia terquemi* and *Marginulina prima* plexi. Also, there was a marked change in the chamber arrangement of younger nodosariid assemblages: uniserial *Nodosaria, Frondicularia* and *Lingulina* were largely replaced by coiled *Lenticulina* (Copestake and Johnson, 1989).

Sample Details

Figure 2 shows the outcrop distribution of the Lower Jurassic in England, together with the location of the sampled sections in England and SW Germany. The Lower Jurassic has a detailed ammonite zonation scheme (Cope et al., 1980) enabling the sections in this study to be zoned with reasonable accuracy. Figure 3 gives details the stratigraphic intervals sampled in NW Europe for this study.

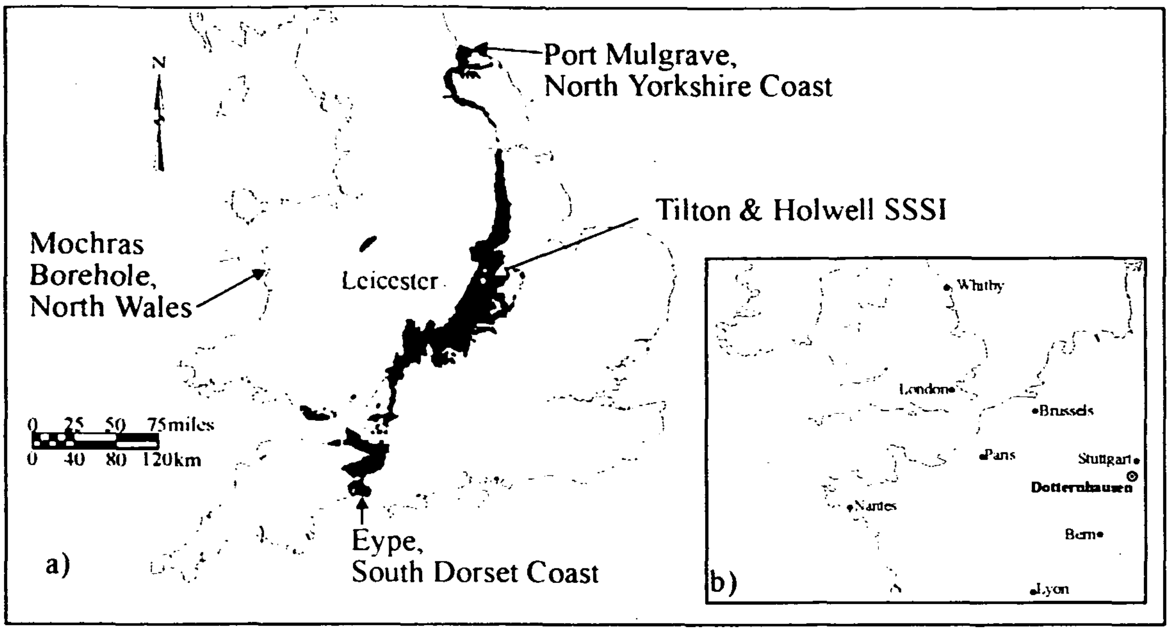


Figure 2. a) Lower Jurassic outcrop in England and location of sections sampled. b) Location of the Dotternhausen Oil Shale Quarry, Baden -Württenburg, S. W. Germany

Along the south Dorset coast, beds of Pliensbachian and Toarcian age are well exposed in accessible cliff sections which have recently been re-measured and described by Hesselbo and Jenkyns (1995). The oldest samples were taken from the Upper Pliensbachian Down Cliff Sands and the Thorncombe Sands. The next six ammonite zones across the Pliensbachian - Toarcian boundary are condensed into the Junction Bed and Marlstone, thin limestone units, which are represented in Yorkshire by 137m of sediment. Above the Junction Bed, Lower Toarcian material was sampled from the Down Cliff Clay.

The section studied at Tilton Railway Cutting in Leicestershire has been described by Hallam (1955). The lowest part of the succession exposes 3m of Upper Pliensbachian silts and clays and the characteristic development of oolitic ironstones of the Marlstone Rock Bed. The base of the Marlstone at Tilton is a non-sequence which represents the whole of the *gibbosus* Subzone, above which the Marlstone is made up of two lithological units: 3m of calcareous and ferruginous sandstones (Sandstone Member) overlain by 2.5m of the Ironstone Member, which is a very oolitic limestone. Howarth (1980) showed that the base of the Toarcian occurs within the Ironstone member, rather than at the 'Transition Bed' level. The Lower Toarcian is represented by 4m of mudstones and clays and lies within the *falciferum* zone (*exaratum* and *falciferum* subzones). A series of samples was taken from the mudstones, clays and shales above and below the Marlstone Rock Bed. North from Tilton a similar exposure is present at the Holwell SSSI. Consisting of two disused quarries conserved as part of a biological and geological reserve, the section exposes nearly 6m of Lower Toarcian laminated shales and mudstones above the Sandstone and Ironstone Members. A series of samples was taken from these sediments comprising the Toarcian *falciferum* zone.

The finely laminated or 'Paper' shales in the *falciferum* zone are analogous to, and roughly coeval with, the Posidonienschiefer of SW Germany and the Jet Rock of the North Yorkshire Coast (Fig. 3). A set of samples from the Whitby Mudstone and Cleveland Ironstone Formations has been provided by C. Little, collected from Port Mulgrave near Whitby. The Lower Toarcian Jet Rock and Bituminous shales of Yorkshire and their equivalents in the North Sea, France (Schistes Cartons), Germany and Switzerland (Posidonienschiefer) are all indicative of periods of deposition of organic-rich shales during the *falciferum* zone (Jenkyns, 1988). The Pliensbachian - Toarcian section sampled in Baden-Württemburg, southwest Germany is thinner and more calcareous than those on the North Yorkshire coast, although it has similar faunal and facies characteristics (Little, 1996).

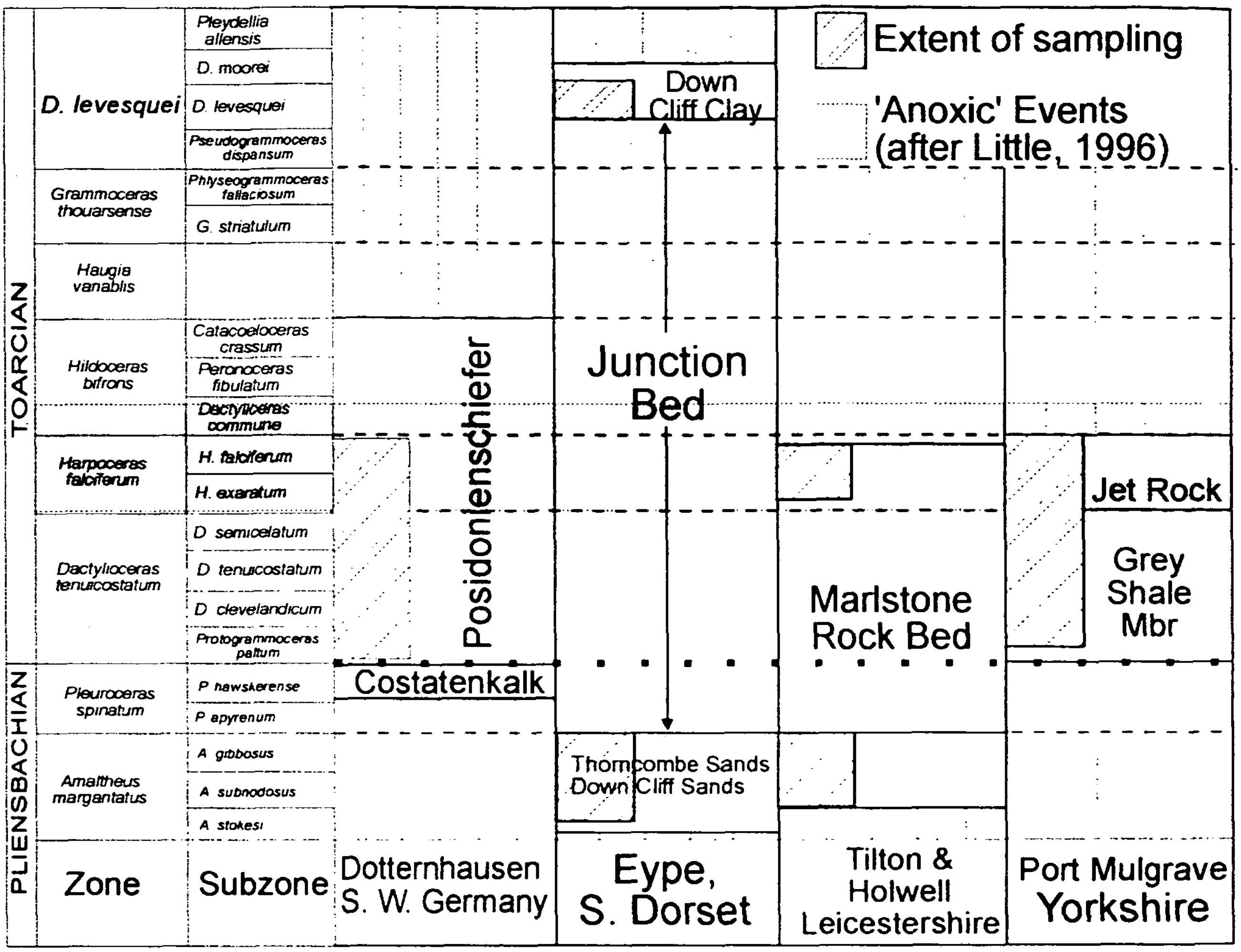


Figure 3. Stratigraphic intervals sampled. Ammonite zonation after Cope et al. (1980).

The main extinction event in south-west Germany occurs towards the top of the *semicelatum* Subzone which is coincident with the most organic-rich part of the Posidonienschiefer and an equivalent facies to the Jet Rock of the Whitby Mudstone Formation. The Posidonienschiefer is well developed in a series of quarries near Dotternhausen which have yielded a rich micro-fauna including foraminifera and ostracods (Riegraf, 1985). For this study, a set of pilot samples, from mid *tenuicostatum* Zone, to the base of the *bifrons* Zone was provided by Dr. Manfred Jäger of Rohrbach Zement.

Overview of Foraminiferal Groups in the Lower Jurassic

The Boreal Realm during the Early Jurassic was characterised by smaller benthic foraminifera. Normal marine shelf assemblages were dominated by nodosariids, with fewer numbers of Miliolina, Robertinidae, Spirillinina, Involutina, Buliminacea, Textulariina, Polymorphinidae and Cassidulinacea (Copestake and Johnson, 1989). Figure 4 illustrates six morphological groups of benthic foraminifera that are considered in this study; these are almost entirely nodosariids except for the Robertiniid genus *Reinholdella*. Within nodosariid-dominated populations, major variances in species and generic abundances are seen in taxa which are long-ranging, suggesting controlling palaeoenvironmental factors. In a statistical analysis of European Lias foraminiferal assemblages, Brouwer (1969) suggested that outer shelf environments were dominated by *Lenticulina* (including *L. muensteri* and *L. varians*), intermediate depths by the *Marginulina prima* plexus and shallower depths by the *Lingulina tenera* plexus.

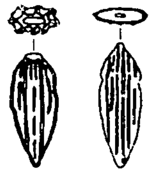
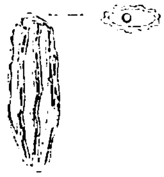
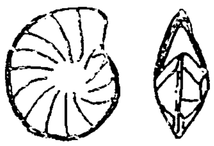
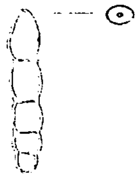
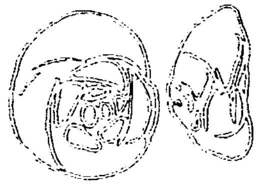
Elongated, flattened *Astacolus* 	Elongated, flattened *Lingulina tenera* plexus group *Frondicularia* 
Elongated, flattened with longitudinal ribs *Marginulina* 	Biconvex (Lenticular) *Lenticulina* 
Elongated, inflated *Nodosaria* 	Bi/plano-convex Trochospiral *Reinholdella* 

Figure 4. Palaeoenvironmentally significant morphologies in Lower Jurassic assemblages of NW Europe.

However, whilst Brouwer's (1969) analysis clearly indicated that distinctive assemblages exist within the overall nodosariid-dominated shelf areas, he had little direct evidence to support his environmental interpretations. This approach was pursued by Muller (1990) who also, through the use of statistical analysis of Lower Jurassic foraminifera, designated thirteen discrete foraminiferal 'biofacies' groups and proposed a model of Liassic benthic foraminiferal palaeobathymetry ranging from very near shore to outer shelf or shelf basins. Again, the *Lingulina tenera* plexus dominated in the inner to near-shore shelf environments while *Lenticulina* gained importance towards more open marine and deeper water environments. *Reinholdella macfadyeni* dominated deeper water areas.

Foraminiferal Response

The distribution of foraminiferal assemblages in comparison with other palaeoecological and sedimentological indicators allows construction of the model in Fig. 5. Palaeodepths of foraminiferal assemblages appear to concur with the eustatic curve proposed by Haq et al. (1987). In addition to the large scale changes in foraminiferal assemblages in response to changing sea-level and environmental conditions, several small scale occurrences have been observed.

At the base of the *exaratum* subzone, (*falciferum* zone) at Tilton, there appears a high abundance of very small (~100µm diameter), trochospiral foraminifera. These are, as yet, unidentified but are similar to the aragonitic genus *Conorboides* which is also reported from the *falciferum* zone of the Upper Lias at Empingham, Rutland (Horton and Coleman, 1977). Given their extremely low abundances before the Toarcian events and their 'bloom' once the environmental conditions markedly decline, this taxon could be described as a *disaster* or *opportunist* species as described by Harries et al. (1996). The species dominates after a rapid transgression in the *exaratum* subzone before the onset of low oxygen conditions.

Similarly, *Reinholdella macfadyeni* occurs in high abundances in the *tenuicostatum* zone of the North Yorkshire Coast. As an indicator of deep water and transgressive events (Brouwer, 1969), *R. macfadyeni* also disappears with the onset of low-oxygen conditions in the Jet Rock.

Recovery of foraminiferal faunas from the Toarcian anoxic events begins during the *falciferum* subzone of the *falciferum* zone. Members of the coiled genera *Lenticulina* and *Astacolus* appear at Tilton in low diversity upper *falciferum* subzone assemblages, while by the *levesquei* zone at Eype, the assemblages have returned to pre-event diversity levels and are dominated by *Lenticulina*, indicating outer shelf, oxygenated conditions.

Assemblages from the Dotternhausen quarries show a decrease in abundance across the Pliensbachian - Toarcian boundary with few extinctions (this study; Riegraf, 1985). The main extinction level occurs in the *semicelatum* subzone of the *tenuicostatum* zone with some species persisting into the middle of the *falciferum* zone. Early *tenuicostatum* zone assemblages are dominated by *Lenticulina* and *Marginulina* with a minor *Nodosaria* component. The development of anaerobic conditions reflected in the Posidonienschiefer (*falciferum* zone) resulted in an absence of any benthic foraminifera and diversity does not recover until the top of the *bifrons* zone, along with the macrofauna (Little, 1996).

While general in its scope, this study also shows that *Lenticulina*, as the most common genus, must have tolerated a very wide range of environmental conditions. Flattened morphologies predominate in low-oxygen conditions which Bernhard (1986) attributed to an increase in surface area to volume which could either minimise the rate of sinking into low-oxygen sediments, or maximise oxygen intake.

A further noticeable trend in foraminifera from low oxygen conditions is towards a reduction in test size. Comparison with Hettangian - Sinemurian assemblages from the UK comprising large species of *Lenticulina*, *Lingulina tenera*, *Nodosaria* and *Marginulina* (Hylton, 1998) shows a decrease in test size of these genera by the Early Toarcian. Having a small test may also maximise relative surface area (Bernhard, 1986). The foraminiferal assemblages from the Down Cliff Clay (*levesquei* zone) at Eype show a return to greater diversity and a larger test size, indicative of more normal, oxygenated conditions. These assemblages are dominated by the *Lenticulina muensteri* plexus group and *Marginulina*.

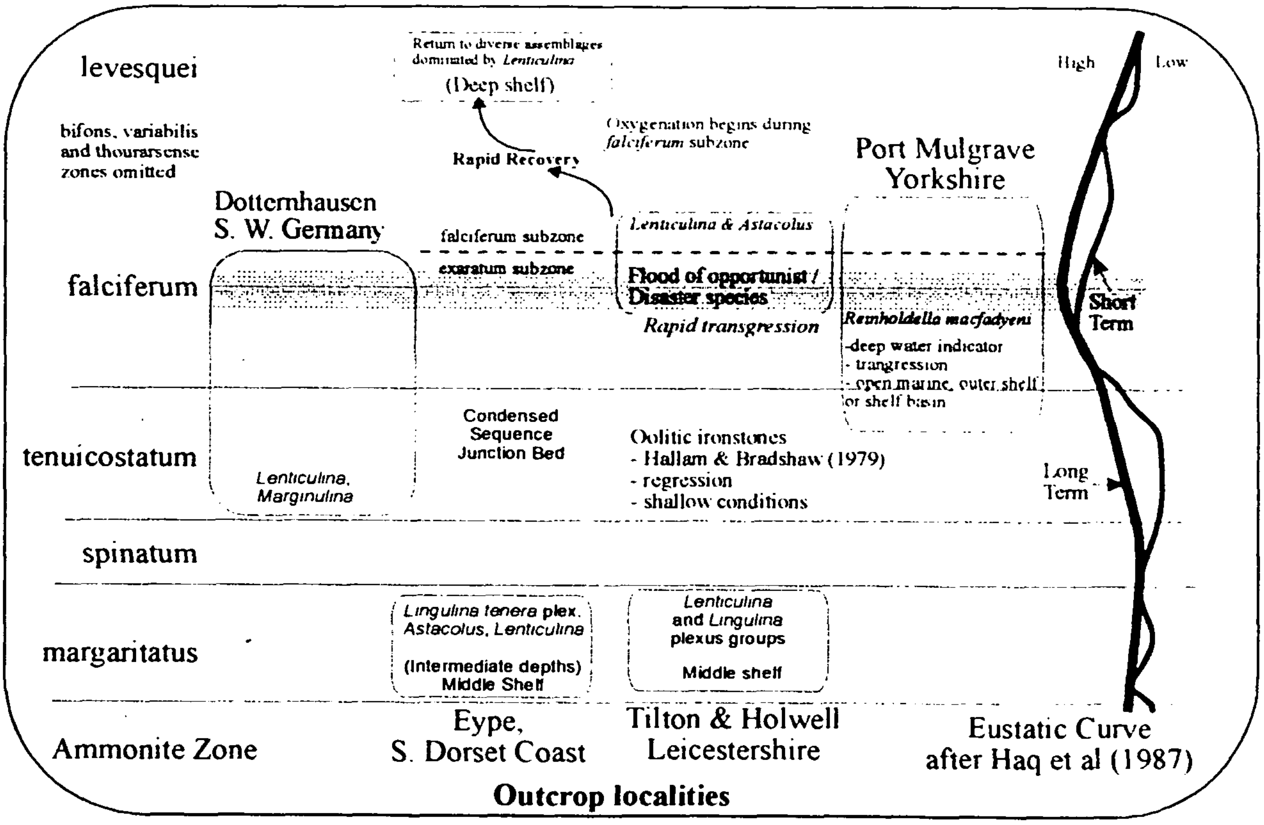


Figure 5. Model of benthic foraminiferal response to environmental conditions in the Late Pliensbachian and Early Toarcian

Conclusions

A fundamental turnover in the foraminiferal assemblage occurs in the *falciferum* zone during which many foraminiferal taxa become extinct. While large scale benthic foraminiferal trends have been previously identified (Brouwer, 1969; Copestake and Johnson, 1989; Brasier, 1988), this high resolution study has revealed the existence of opportunist or disaster foraminiferal species. These species occur during times of environmental stress and exploit available habitat space for short periods of time.

Interpretations of Early Jurassic palaeoenvironments based upon foraminiferal associations generally match sea-level curves and agree with sedimentological evidence. The response of benthic foraminifera during the Late Pliensbachian - Early Toarcian can be linked to changes in sea-level and the resulting development of low oxygen conditions. Uniserial forms such as *Nodosaria*, *Frondicularia* and *Lingulina*, which dominate Pliensbachian assemblages, become less important in Toarcian and subsequent assemblages, whereas the coiled forms like *Lenticulina* dominate after the event. Generalists such as *Lenticulina* most likely had certain adaptations that allowed them to survive low oxygen conditions and contribute to the rapid recovery that started in the *falciferum* subzone.

This study continues with further investigation of Upper Pliensbachian - Lower Toarcian sections in the United Kingdom, South West Germany and southern France.

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