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THE TIMING OF PALEOENVIRONMENTAL CHANGE AND CAUSE-AND-EFFECT RELATIONSHIPS DURING THE EARLY JURASSIC MASS EXTINCTION IN EUROPE

PAUL B. WIGNALL[†], ROBERT J. NEWTON and CRISPIN T.S. LITTLE

School of Earth Sciences, University of Leeds, Leeds LS2 9JT, United Kingdom; wignall@earth.leeds.ac.uk

ABSTRACT. The early Jurassic marine mass extinction is one of several crises thought to coincide with anoxia, transgression and warming caused by catastrophic release of gas hydrates. However, high-resolution study of expanded sections in Yorkshire, England, reveal that only the first of these factors is truly coincidental with extinction. The well known transgression and large, negative carbon isotope perturbation, attributed to massive release of methane from gas hydrates, occur after these events. The anoxic event is developed diachronously in the European area, with anoxia developing and fading away earlier in the Mediterranean region compared with the NW European record. However, for a brief interval (in the mid *semicelatum* Subzone), anoxia was simultaneously developed throughout the European region and it is this time that is marked by extinction of both benthic and pelagic marine fossils. The sea-level curve is also more complex than hitherto assumed, with a minor regression occurring late in the *semicelatum* Subzone, shortly after the extinction. The Toarcian crisis occurred during a phase of global warming, but the postulated release of methane from gas hydrates is too late to be implicated in the extinction mechanism as indeed is a recently reported cooling event from within the warming trend.

INTRODUCTION

Mass extinctions commonly coincide with a range of environmental events including oceanic anoxia, eustatic sea-level rise, rapid global warming, large igneous province eruptions and carbon cycle perturbations (see for example, Hallam and Wignall, 1997, 1999; Kerr, 1998; Pálfy and Smith, 2000; Wignall, 2001; Hesselbo and others, 2002; Courtillot and Renne, 2003). Linking these varied phenomena into integrated models has become a major goal in Earth system science. In particular, the release of vast volumes of methane from gas hydrate, triggered by volcanogenic warming, is postulated to have had catastrophic effects in many extinction scenarios (see for example, Retallack, 1999; Hesselbo and others, 2000; Ryskin, 2003). The Early Jurassic (Toarcian) mass extinction event provides one of the best test cases of these integrated extinction models because the availability of a high resolution ammonite biostratigraphy enables the cause-and-effect chain of events to be tested within a detailed time frame.

Many authors have postulated that the emplacement of the Karoo-Ferrar large igneous province in southern Gondwana triggered global warming, although recent dating suggests it may have been a more prolonged, and therefore less catastrophic, eruption event (Jourdan and others, 2005). A rapid, negative, carbon isotope excursion provides evidence for the release of the methane into the ocean-atmosphere system (Hesselbo and others, 2000; Jenkyns and others, 2002; McElwain and others, 2005; Kemp and others, 2005). This excursion coincides with rapid transgression and the acme of the Toarcian anoxic event in the *Eleganticeras exaratum* Subzone (Wignall, 1991; Hallam, 1997; Hallam and Wignall, 1999; Frimmel and others, 2004). The latter phenomenon has been postulated to be an ocean-wide phenomenon (Jenkyns, 1988) and is often held as the cause of the coeval marine mass extinction (Hallam, 1987;

[†] Corresponding author

Little and Benton, 1995; Hallam and Wignall, 1997; Jenkyns, 1999, 2003; Pálfy and Smith, 2000; Bucefalo Palliani and others, 2002). There are several potential causal links between global warming and marine anoxia (see Wignall and Twitchett, 2002), but the increased run-off of terrigenous nutrients in a warmer climate, with consequent eutrophication of shelf seas, is often regarded as the most likely cause-and-effect (Jenkyns, 1999; Pálfy and Smith, 2000; Jenkyns and others, 2002; Cohen and others, 2004).

PROBLEMS OF TIMING

Despite the plausible scenario for the cause of the Toarcian extinction crisis, substantial problems exist with the timing details that are potentially fatal to the model. These fall into three categories:

1) The ages of black shales appear to be different in northern (Boreal) Europe compared to southern (Tethyan) Europe.
2) The timing of the extinction appears to vary between Boreal and Tethyan realms and between benthic and pelagic groups.
3) The reported sea-level history is different between Boreal and Tethyan areas.

Timing of Anoxia

Due to the provinciality of ammonite faunas, somewhat different ammonite zones and subzones are used in Mediterranean (Tethyan) and north-west European (Boreal) provinces (fig. 1). However, there is a consensus amongst ammonite workers that the boundaries of the *D. tenuicostatum* and *H. serpentinum* zones of northern Europe are coeval with the *D. polymorphum* and *H. serpentinum* zonal boundaries of the Mediterranean region (Macchioni, 2002; Page, 2004; fig. 1).

The best-dated Tethyan sections are in Italy and Spain where the black shales occur within the *Dactylioceras semicelatum* Subzone of the basal Toarcian *Dactylioceras polymorphum* Zone (fig. 1; Jiménez and others, 1996; Nini and others, 1997; Bucefalo Palliani and others, 1998, Macchioni, 2002; Rosales and others, 2004). This was followed by the widespread development of the "Rosso Ammonitico" deep-water condensed limestone facies deposited in well oxygenated conditions during the *Harpoceras serpentinum* Zone (Mattioli and Erba, 1999). In contrast, the Toarcian black shales of northern Europe belong to the *H. serpentinum* Zone, known as the *Harpoceras falciferum* Zone in the older literature (Howarth, 1962; Hallam, 1967; Jenkyns and Clayton, 1986; Jenkyns and others, 2002), although anoxic facies are known to have begun within the latest *D. semicelatum* Subzone in some sections (see for example, Wignall, 1991).

Jenkyns and colleagues consider biostratigraphic correlation to be in error in the Toarcian and argue for the synchronous development of black shales throughout Europe (see for example, Jenkyns and Clayton, 1986, 1997; Jenkyns and others, 2002). They suggest that this can be demonstrated by using the first occurrence (FO) of the ammonite *Hildaites* as an isochronous marker (fig. 1). This taxon's FO is in the upper *D. semicelatum* Subzone in the Mediterranean area, but it appears slightly higher in German sections near the base of the *E. exaratum* Subzone (Macchioni, 2002). In England, *Hildaites* appears higher still, in the later part of the *E. exaratum* Subzone (Howarth, 1992a, 1992b). However, even if the FO of this genus is taken to be synchronous, as shown in the alternative correlation in figure 1, it fails to prove a synchronous onset of black shale deposition. This is because *Hildaites* appears after black shale development in the Mediterranean, at the onset of it in Germany and within the black shale unit in England. The first occurrence of *Hildaites* more likely reflects the slow northward migration of this Tethyan ammonite and/or the extreme rarity of this taxon in the Boreal Realm.

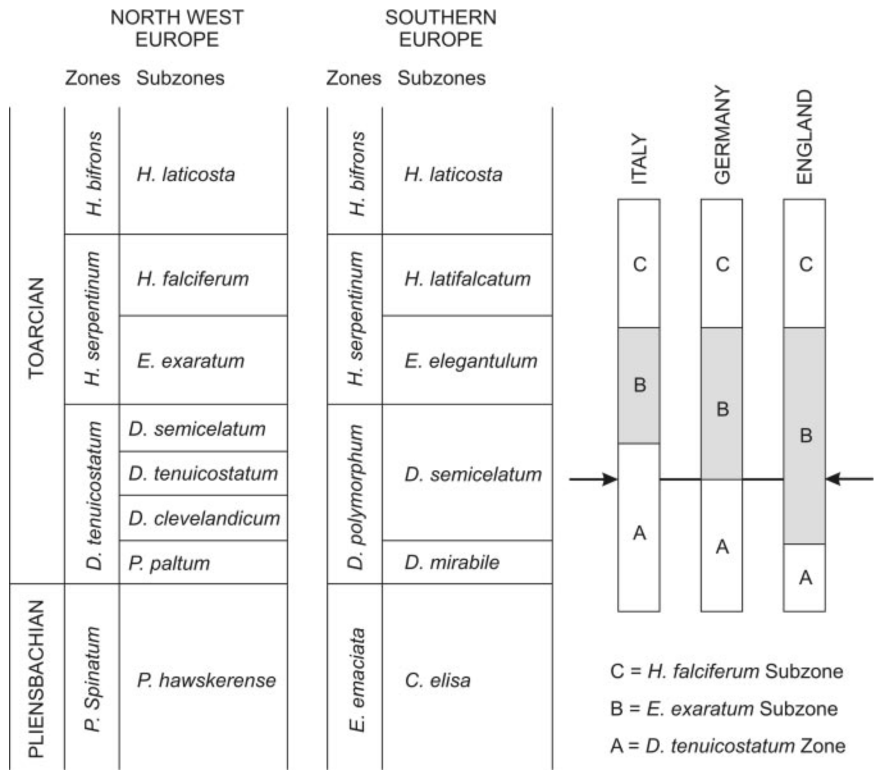

Fig. 1. Correlation of ammonite zones and biozones in Europe (Macchioni, 2002; Cecca and Macchioni, 2004; Page, 2004). The right-hand columns show the alternative correlation of Toarcian subzones proposed by Jenkyns and others (2002). This is based upon the first appearance of *Hildaites* spp. (arrowed level) and the assumed coincidence of negative carbon isotope excursions. A disadvantage of this alternative scheme is that the first and last appearances of all other ammonite taxa becomes diachronous.

The assumption of a synchronous black shale event in Europe is impossible to reconcile with other ammonite evidence (see for example, Jiménez and others, 1996; Nini and others, 1997; Macchioni, 2002; Cecca and Macchioni, 2004; Page, 2004). For example, the first occurrence of *Eleganticeras elegantulum* is used to define the base of the *H. serpentinum* Zone in Europe. In the Umbria-Marche Basin of northern Italy this ammonite first appears above the black shale development whereas it occurs near the base of the black shales in both Germany and England (Macchioni, 2002). The sections of the Basque-Cantabrian Basin in northern Spain provide equally irrefutable evidence for black shale diachroneity. Here black shales are only encountered in the early *D. semicelatum* Subzone (Rosales and others, 2004).

Other than the FO of *Hildaites,* the main argument for a synchronous black shale development comes from correlation of C isotope excursions that are presumed to be a global record (see for example, Hesselbo and others, 2000; Kemp and others, 2005). A negative excursion has been identified in the *E. exaratum* Subzone of many NW European Toarcian sections and at least one good example of this excursion is known from northern Italy (Jenkyns and others, 2001). In all cases the sharp, negative excursion is encountered at the onset of deposition of black shale facies, and this is used as evidence for their synchroneity. However, there is an alternative (non-global) explanation for the negative excursions.

Many authors (arguably the majority), have suggested that the negative excursion reflects basin restriction and the associated recycling of ^{12}C-enriched dissolved inorganic carbon from the lower water column (see for example, Küspert, 1982; Jenkyns, 1988; Hollander and others, 1991; Sælen and others, 1996, 1998, 2000; Schouten and others, 2000; McArthur and others, 2000; Röhl and others, 2001; Schmid-Röhl and others, 2002; van de Schootbrugge and others, 2005). This hypothesis is testable because the negative excursion should not be present in sections lacking black shales, and this is indeed what is observed. For example, the $\delta^{13}C_{org}$ data presented by Jenkyns and others (2001) shows a sharp, negative excursion of 7 permil at two British localities (Mochras Farm and Hawsker Bottoms) where black shales are developed, but no excursion at Winterborne Kingston where black shales are not seen. It is significant that the excursion is also not recorded from belemnite calcite, even when these fossils are collected from black shales (van de Schootbrugge and others, 2005). Such free-swimming coleoids probably migrated long distances, like modern squid, and so may have avoided growing in the harsh conditions of the Cleveland Basin, thereby not acquiring a light C isotopic signature.

The only non-black shale dataset to record the excursion is that of Hesselbo and others (2000) who show a gradual, 6 permil shift in terrestrial organic matter from a Danish paralic section. This can only be tentatively correlated with the marine sections of the Cleveland Basin and it remains to be seen if this trend is replicated in other sections.

What Went Extinct and When?

The best Early Toarcian extinction record comes from the relatively expanded, basinal section of North Yorkshire, England where it has been shown that benthic extinctions occurred late in the *D. tenuicostatum* Zone (Hallam, 1987; Little and Benton, 1995; Little, 1996; Harries and Little, 1999; Hylton and Hart, 2000). One of the most significant benthic losses in the Toarcian, the brachiopod order Athyridida, occurred slightly later in the *E. exaratum* Subzone of southern England (Vörös, 2002). In contrast, the main ammonite extinctions in these Boreal latitudes occurred earlier, at the Pliensbachian/Toarcian Stage boundary (Little and Benton, 1995; Cecca and Machioni, 2004).

Remarkably, the extinction record from Tethyan southern Europe is the opposite to that seen in NW Europe with benthic extinctions preceding pelagic ones. Various benthic groups (brachiopods, foraminiferans, ostracods) of southern Europe suffered significant extinctions from the latest Pliensbachian to the the early *D. polymorphum* Zone followed by radiation early in the *H. serpentinum* Zone (Bassoullett and Baudin, 1994; Nocchi and Bartolini, 1994; Vörös, 1995; Boomer and others, 1998; Herrero, 2001). The extinction interval coincides with a Tethyan biocalcification crisis in surface waters (Dromart and others, 1996; Mattioli and others, 2004; Tremolda and others, 2005). The epioceanic Tethyan ammonite species suffered a major extinction event late in the *D. polymorphum* Zone after the benthic losses (Cecca and Macchioni, 2004). It is noteworthy that the foraminiferal record of central Tethys (NW Caucasus) also reveals a radiation in the *H. serpentinum* Zone following a preceding extinction event, suggesting that there was a widespread Pliensbachian/Toarcian boundary crisis in the marginal basins of the Tethyan Ocean (Ruban and Tyszka, 2005).

The *H. serpentinum*-Zone age anoxia of Boreal Europe therefore coincides with post-extinction recovery in Tethys. As recognized by many (see for example, Guex and others, 2001; Bailey and others, 2003; Rosales and others, 2004), this is a serious problem for any anoxia-extinction nexus. Thus, cooling and regression at the end of the preceding Pliensbachian Stage, related to the eruption of the Karoo-Ferrar flood basalt province, has been postulated as the main cause of the extinction (Guex and others, 2001; Rosales and others, 2004).

Sea-level Change

The European Toarcian record is marked by a major transgression following an end-Pliensbachian regression (Hallam, 1997). In England and Germany this base-level rise saw the extensive spread of mudrock deposition over a vast area (Wignall, 1991; Wignall and Maynard, 1993). In contrast, in southern Europe, transgression at the base of the *D. polymorphum* Zone is followed by regression at the top of this Zone (Jiménez and others, 1996; Parisi and others, 1996; Perilli, 2000; Macchioni, 2002; Mattioli and Pittet, 2004). Thus, in basin margin sections, a sequence boundary marks the base of *H. serpentinum* strata (Perilli, 2000; Mattioli and Pittet, 2004). The formation of this sequence boundary coincides with the onset of black shale deposition in northern Europe, casting some doubt on the link between transgression and anoxia.

AIMS

This work attempts to resolve these complex issues by investigating the detailed timing of early Toarcian paleoenvironmental and paleontological events in the basinal mudrock sections of the Cleveland Basin (North Yorkshire, England, fig. 2). These provide the most expanded and therefore most detailed early Toarcian record in Boreal latitudes. By constraining the precise level of benthic extinctions, and comparing this with evidence for relative sea-level change, facies changes, redox fluctuations and previously published paleotemperature and carbon isotope values it has been possible to demonstrate a detailed history of events during the Early Toarcian crisis in this region. The results vindicate the link between anoxia and extinction but contradict many other proposed cause-and-effect relationships.

ANALYTICAL APPROACH

Detailed sedimentary logs of late *D. tenuicostaum*—early *D. serpentinum* strata were made at four coastal sections in North Yorkshire (Port Mulgrave, Runswick Bay, Kettleness, Hawsker Bottoms) straddling the boundary between the Grey Shales and Jet Rock members (fig. 2). As with previous studies of these rocks, Howarth's (1962, 1973) bed numbering scheme was used. Grain size determinations were made in the field and corroborated in thin section and by assay of Si/Al ratios. Silt lamina thickness was measured and sedimentary structures identified where present. At some levels bioturbation has partly or completely destroyed the primary sedimentary fabric and Droser and Bottjer's (1986) ichnofabric index classification scheme was used to semi-quantify this feature. The benthic fossil occurrence was assessed on a decimeter scale and identified to species level where possible. Total organic carbon values were derived from Rock Eval pyrolysis. A field-portable gamma-ray spectrometer enabled the measurement of concentrations of K, Th and U in the field as described by Myers and Wignall (1987). Scanning electron microscopy of polished blocks was used to assess size frequency distributions of pyrite framboids (Wignall and Newton, 1998). Iron geochemistry can also provide valuable redox indicators and both the degree of pyritization (DOP) of iron and index of anoxia (IA) were assessed (Raiswell and others, 2001).

RESULTS

An identical succession of changes was seen in all the studied sections and only the data for the Kettleness section are presented here, because it is the best exposed section.

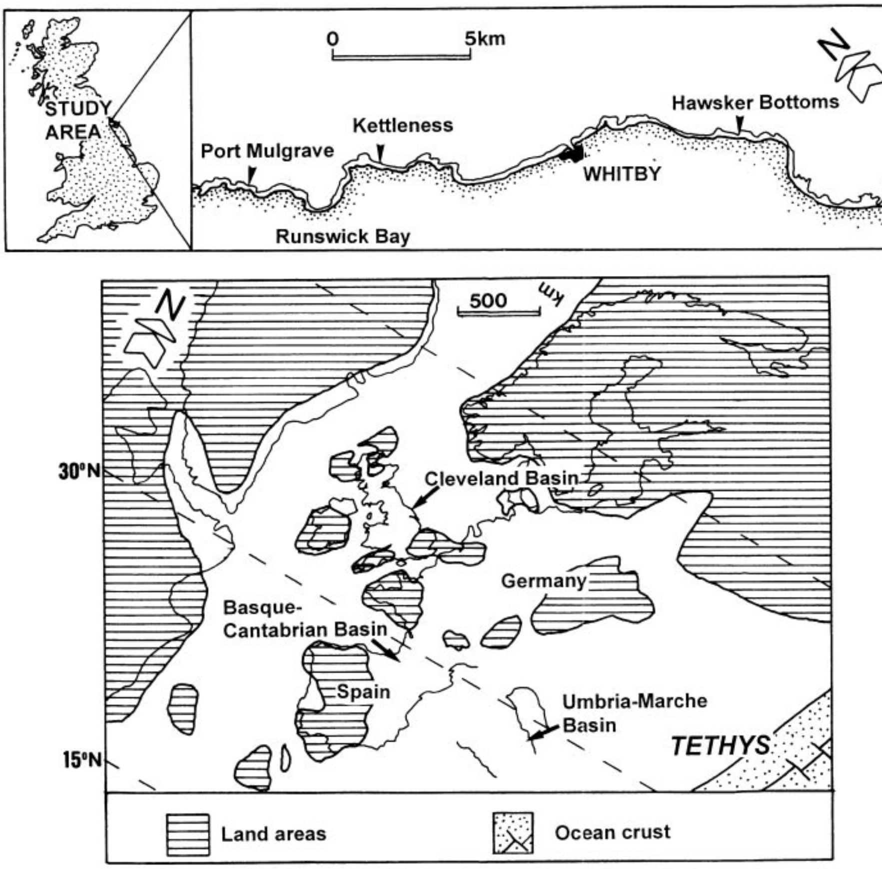

Fig. 2. Location map of the studied sections in the Cleveland Basin, and the Early Jurassic paleogeography of western Europe (from Bassoullet and others, 1993).

Fossil Ranges

A diverse benthos ranges upwards throughout the Grey Shales until the lower part of Bed 31 where the majority of the fauna disappears (fig. 3). Other than *Oxytoma inequivalve*, an exceptionally long-ranging species that persisted to the early Cretaceous, these disappearances are last occurrences. The extinction level coincides with the gradual onset of laminated deposition (see below) and the establishment of a low diversity/high abundance fauna of epibenthic bivalves. Initially, *Bositra radiata* is encountered but, from the base of Bed 32 up into the basal beds of the Jet Rock, *Pseudomytiloides dubius* is the only benthic species present, albeit in great numbers. Ammonites are common throughout the study interval and their ranges have been reported previously (Howarth, 1992a, 1992b; Little and Benton, 1995; Harries and Little, 1999; Cecca and Macchione, 2004). The main ammonite extinctions are at the Pliensbachian/Toarcian stage boundary, below our study interval, and there is no major (that is, generic-level) extinction of ammonites coincident with the benthic species extinction event higher in the Toarcian.

Sedimentology

The 13.5 m-thick Grey Shales Member mainly consists of silty mudstones with some thin beds of silt-laminated, organic-rich shale in its basal part (Wignall, 1994).

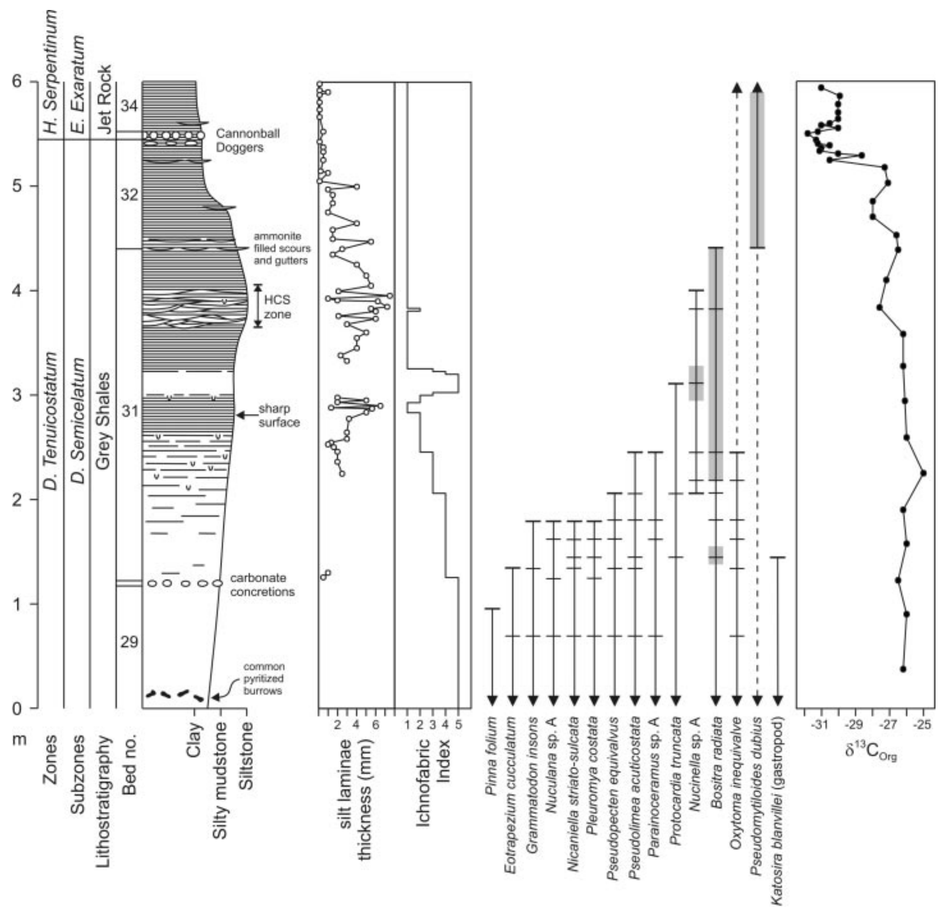

Fig. 3. Sedimentary log through the early Toarcian mass extinction interval at Kettleness, North Yorkshire, UK (NZ 8360 1595), showing silt laminae thickness (intervals without data lack laminae due to bioturbation), ichnofabric index (1 – no burrows, 5 – thorough bioturbation), benthic macrofaunal species ranges (shaded where prolific) and organic C isotopic fluctuations from (Hesselbo and others, 2000). HCS is hummocky cross stratification, and the Cannonball Doggers are spherical concretions. Bed numbering scheme is Howarth's (1962, 1973).

The uppermost 7.5 m consists of a coarsening-upward unit that begins as mudstone and culminates in a siltstone around 1.5 m from the top of the Member (fig. 3). The coarsening-up is seen as both an increase in quartz silt content in thin section and an increase in Si/Al ratios from 1.7 at the base to 3.0 at the top of the unit. The uppermost part of Bed 31 and Bed 32 fines upwards to essentially silt-free shale in just over 1 m of section (fig. 3).

Below Bed 31 bioturbation is pervasive in the upper Grey Shales (ichnofabric index 5) but, from the base of bed 31 upwards, burrowing intensity declines and primary laminations of thin, sharp-based, graded, silt laminae are progressively better preserved. Silt lamina thicknesses increase upwards from the base of Bed 31 where they can first be discerned. In the coarsest interval (maximum grain size 1 ø) of Bed 31 the silt laminae are erosive-based, with up to 3 cm of erosive relief (fig. 4). In some cases the erosive hollows are infilled with broad hummocks displaying peak aggradation above the erosive lowpoints. This is a characteristic feature of hummocky cross

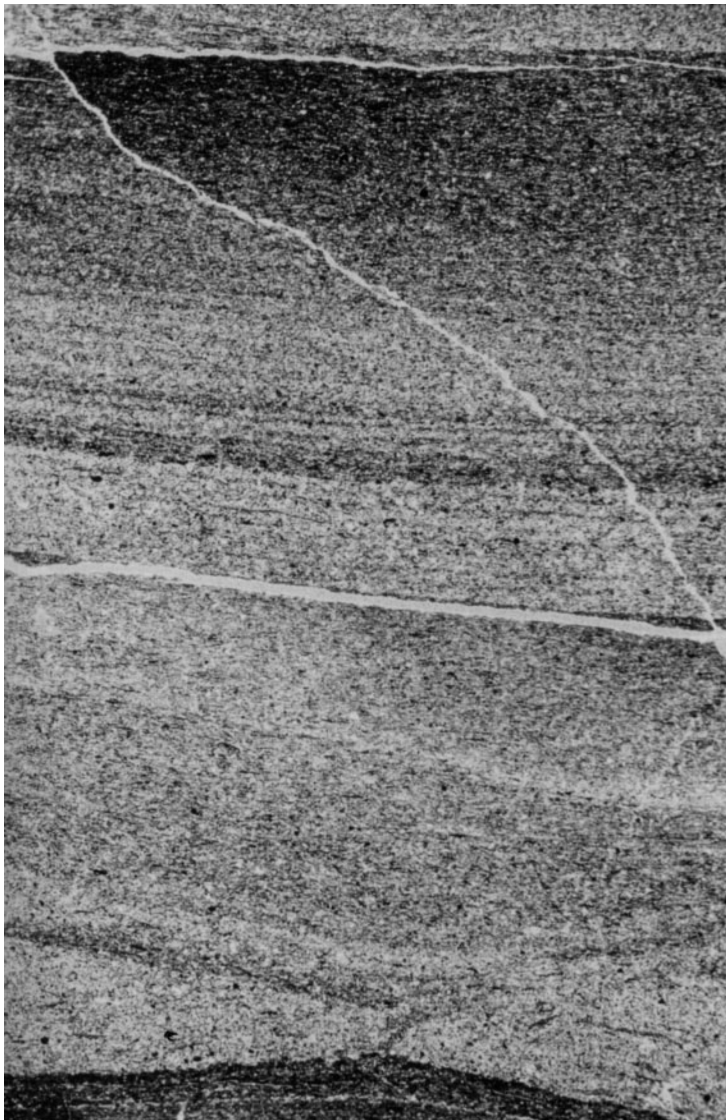

Fig. 4. Photomicrograph of an erosive-based silt laminae from the top of Bed 31 at Kettleness. Above the erosion surface the silt lamination displays migration to the right recording the aggradation and lateral expansion of the flanks of a small hummock following seafloor erosion. Field of view is 8mm wide and 12 mm tall.

stratification (HCS), albeit on a small scale in these examples. The "current laminated features" described and illustrated by O'Brien (1990) from this level may be from the flanks of these broad, low amplitude hummocks. In the Port Mulgrave section a few horizons with starved, oscillatory ripples are also developed 60 cm below the HCS strata. In the fining-upward succession, beginning around the Bed 31/32 boundary, silt laminae become increasingly thinner and more widely spaced (fig. 3). Broad scours and gutters infilled with both complete and finely fragmented ammonites are the most

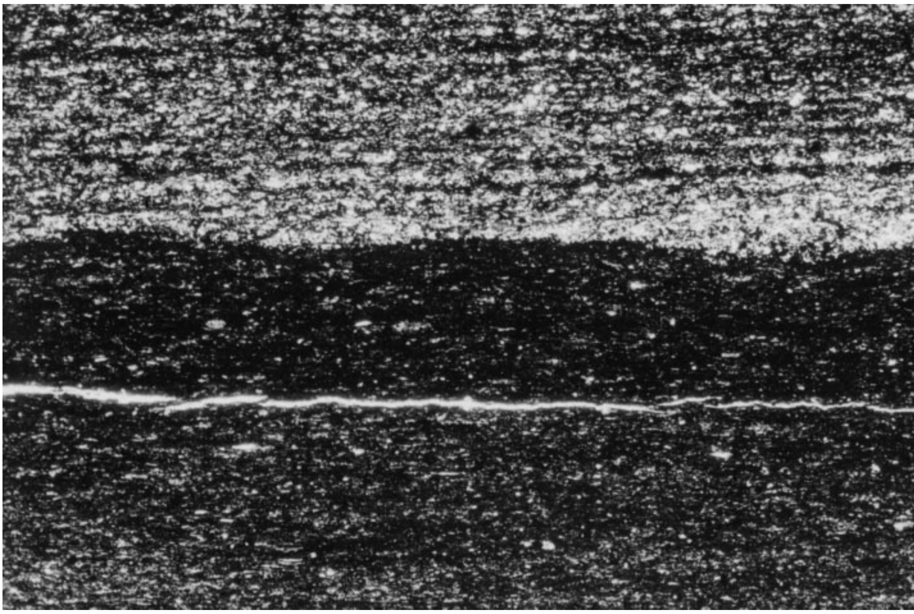

Fig. 5. Photomicrograph of a thin section from the upper part of Bed 32 at Port Mulgrave, showing the two main types of lithology. These consist of a homogenous fabric primarily composed of dark clay minerals and organic matter (lower two thirds of field of view) displaying a compacted but not laminated fabric and silt-laminated level. Field of view is 5.5 mm wide.

obvious manifestation of current activity at this level, and they range up into the basal 20 cm of the Jet Rock.

In Bed 32 and in the basal beds of the Jet Rock the sediment consists of alternations of silt laminae and "background" sediment composed of clay and mica minerals, fine-grained silt, organic matter, and dispersed pyrite grains (see for example, fig. 6 of Pye and Krinsley, 1986). Lamination is not seen in thin section although a well-developed compacted/aligned fabric is displayed (fig. 5). However, at some levels fine lamination, varying from 0.5 to 3.0 mm in thickness, is visible in hand specimen and polished blocks (and also in the X-radiographs of Pye and Krinsley, 1986). This is defined by subtle fluctuations in the organic matter content and, unlike the sharp-based silt laminae, the contacts of the laminations are gradational.

Redox Indicators

As seen in many previous studies, the total organic carbon (TOC) values of the Jet Rock are substantially higher than those seen in the underlying Grey Shales. The increase is a gradual one that begins in the base of Bed 31 (fig. 6). However, the TOC values of the uppermost Grey Shales may be "diluted" by the high silt content at this level. Careful selection of a silt-poor lamina from the basal laminated interval of Bed 31 revealed a TOC value (7.5%) comparable to that found in the Jet Rock (fig. 6). Reported, hydrogen index values in the North Yorkshire sections vary somewhat from study to study although all show a general increase in the late *D. semicelatum* Subzone (Sælen and others, 2000; Bucefalo Palliani and others, 2002), consistent with the onset of oxygen-restricted deposition.

Pyrite framboids are common in the uppermost Grey Shales and Jet Rock. Their mean diameters and range of sizes declines with the onset of laminated deposition and remains constant above this level (fig. 6). Th/U ratios, calculated from gamma-ray

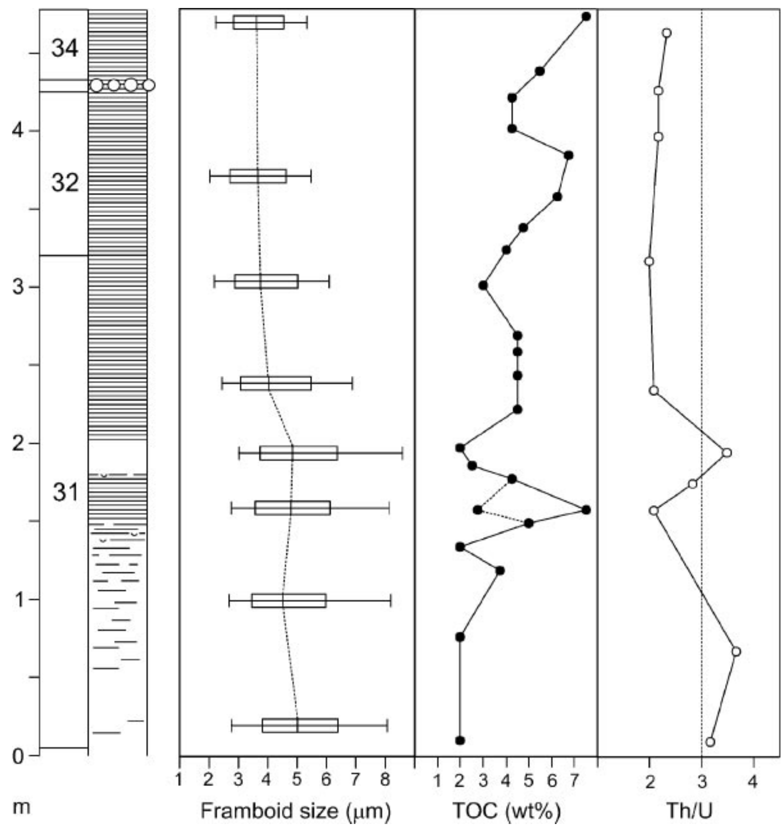

Fig. 6. Measures of oxygenation through the extinction interval at Kettleness. Pyrite framboid diameters are plotted as box-and-whiskers showing 25th and 75th percentiles and the median. The "whiskers" denote the 10th and 90th percentiles, sample size varies from 178 to 261. The total organic carbon (TOC) weight % values are for whole rock samples except at 1.5 m where a lower whole rock value is contrasted with a sample in which silt laminae were removed prior to analysis. The Th/U ratio is calculated from gamma-ray spectrometer data.

spectrometry data show a similar dichotomy with values greater than 3 in the bioturbated strata and consistently around 2 in the laminated strata (fig. 6). The subtlety of this measure is seen in the brief return to Th/U values greater than 3 in the 20 cm-thick burrowed horizon developed close to the base of the laminated section.

Both IA and DOP increase in the upper part of the *D. semicelatum* Subzone. The index of anoxia increases from values around 0.3 to values of 0.75. The degree of pyritization is more variable but generally below 0.75 in the bioturbated strata and above this value in the laminated strata of the uppermost Grey Shales and Jet Rock (Newton, ms, 2001).

DISCUSSION

Anoxia and Extinction

All redox indicators indicate the establishment of anoxic deposition within Bed 31. Thus, the loss of most benthic species in the middle of Bed 31 coincides with the dramatic decline of burrowing activity, with a consequent preservation of lamination. Increase of TOC and HI values at the same level indicates improved organic matter preservation, typical of anoxic deposition. Inorganic geochemical indicators show an increase of IA and DOP and a decline of Th/U ratios that again are readily explained by the development of anoxic bottom waters. Anoxic conditions have long been invoked for the overlying Jet Rock (see for example, Hallam, 1967), and also for the uppermost part of Bed 32, but the recognition that these conditions began within Bed 31 (mid *D. semicelatum* Subzone) indicates that onset of anoxia was earlier than previously appreciated. Jet Rock deposition is commonly regarded to have been euxinic (see for example, Sælen and others, 2000; Jenkyns and others, 2001) and pyrite framboid data indicate that the euxinicity began within the mid *D. semicelatum* Subzone. A decline of pyrite framboid size is seen in modern oxygen-restricted environments when the site of their genesis at the redox boundary moves from the sediment to within the water column (Wilkin and Barnes, 1997). In the Grey Shales, pyrite framboid sizes and mean diameters show a gradual decline beginning in the middle of Bed 31 and, by the top of this Bed, populations remain unchanged up into the overlying Jet Rock (fig. 6).

Within the laminated portion of Bed 31 the 20 cm-thick bed of bioturbated strata indicates a transient improvement of bottom-water oxygenation, as does the increase of Th/U ratios. *Nucinella* sp. nov. is abundant at this level and this species, which appears around the extinction level and disappears a short distance higher in the section, can be considered a disaster taxon. The presence of two species of bivalves, *Bositra radiata* and *Pseudomytiloides dubius*, in the laminated, organic-rich shales has long-proved a cause of controversy, with competing models of benthic and pelagic life sites proposed (see summary in Wignall, 1994). More recent appreciation of the dichotomy between geochemical and palaeoecological data can help diffuse this debate (Raiswell and others, 2001). Geochemical indicators generally record long-term (that is, average) depositional conditions, which in the case of Jet Rock and upper Grey Shales was clearly euxinic. In contrast, fossils only record conditions during the (geologically) brief moment they were alive. Thus, it is possible to envisage the bivalves colonizing during brief seafloor oxygenation events that punctuated the long-term euxinicity.

Previous studies of the North Yorkshire sections have suggested that the peak intensity of Toarcian anoxia was restricted to the *E. exaratum* Subzone, based on the peak of TOC values at this level (see for example, Jenkyns and Clayton, 1997; Jenkyns and others, 2002). However, TOC values are affected by several factors including dilution by silt content. Dilution-independent criteria including hydrogen index values and pyrite-framboid sizes, indicate that intense oxygen-restriction began within the *D. semicelatum* Subzone and persisted into the *E. exaratum* Subzone.

The onset of oxygen-poor conditions is earlier than previously reported but it precisely coincides with the benthic extinctions (fig. 3), supporting the long-proposed link between these two phenomena (Hallam, 1986, 1987). Bucefalo Palliani and others (2002) report the temporary loss of all calcareous nannofossil species and the loss of 7 out of 10 dinoflagellate cyst species during the late *D. semicelatum* Subzone, indicating that the crisis also severely affected some life in the upper water column, although curiously not the ammonites.

Sea-level Change

The development of deep-water facies in the Toarcian of North Yorkshire is clear evidence for a major transgression (Hallam, 1997). However, in detail, the Cleveland Basin record suggests that the onset of anoxia occurs within a small-scale regressive cycle that culminated with the development of storm and wave-influenced facies. The gradual disappearance of silt laminae at the top of the *D. semicelatum* Subzone (Bed 32) and the associated grain size decrease, indicates renewed deepening and waning influence of storm activity after the onset of oxygen-restricted deposition.

With this interpretation the relative sea-level history of the Cleveland Basin becomes remarkably similar to that recorded from Tethyan locations where there is also a sea-level fall of latest or terminal *D. tenuicostatum* Zone age (Perilli, 2000; Mattioli and Pittet, 2004). This regression is superimposed on the generally transgressive Toarcian trend but it nonetheless highlights the important point that the development of Toarcian anoxia was not closely related to sea-level change. The relationship between anoxia and temperature trends is closer but equally intriguing.

Paleotemperature Trends

Several, high resolution, geochemical temperature proxies are available for the Pliensbachian-Toarcian interval. Ratios of Ca/Mg and $\delta^{18}O$ obtained from belemnites of the Basque-Cantabria Basin of northern Spain indicate that a warming trend began at the base of the *D. tenuicostatum* Zone and peaked early in the *H. serpentinum* Zone (Rosales and others, 2004). Fossil data support this interpretation because a major northward migration of Tethyan ammonites and brachiopods also begins at this time (Macchioni and Cecca, 2002; Vörös, 2002; Cecca and Macchioni, 2004). Data from NW Europe indicate a similar trend, but beginning somewhat later in the mid *D. tenuicostatum* Zone (Bailey and others, 2003).

The anoxia in both Tethyan and Boreal regions can thus be seen in the context of a long-term regional warming trend. In sharp contrast, McElwain and others (2005, p. 481) have suggested that the *E. exaratum* Subzone anoxia may have occurred during a time of sharp cooling, "possibly of a sufficient magnitude even to enable transient ice cap growth at higher elevations of northern and southern latitudes of Pangaea". However, there is no evidence for a glacioeustatic regression at this time and their conclusions are based solely on stomatal index data. These show a spectrum of values indicative of a broad range of atmospheric CO_2 concentrations.

Carbon Isotope Trends

The cause of substantial oscillations of Toarcian C isotope values has proved highly controversial. The highest resolution and most detailed data are from the Cleveland Basin. These reveal several, sharp negative shifts of organic C $\delta^{13}C$ values in the latest *D. semicelatum* Subzone to early *E. exaratum* Subzone, followed by a shift to heavier values in the late *E. exaratum* Subzone (Hesselbo and others, 2000; Kemp and others, 2005). As noted above, the lighter isotopes are only found in anoxic facies and they are probably a signature of stratification of the water column as first proposed by Küspert (1982). In contrast, the positive excursion is more widely recorded (van de Schootbrugge and others, 2005), even in sections lacking anoxic strata. It is tempting to relate this to the enhanced burial of organic C during a Toarcian oceanic anoxic event (see for example, Jenkyns, 1988; Jenkyns and others, 2002), but it does not correlate closely with black shale deposition in Europe because the positive trend occurs after the main phase(s) of organic-rich deposition.

The type example of oceanic anoxic events occurs around the Cenomanian-Turonian boundary of the Cretaceous. Here too the timing of the associated C isotopic excursion does not match the region-by-region development of anoxia. Bowman and Bralower (2005) have therefore suggested that the Cretaceous $\delta^{13}C$ trend records the oceanic (rather than shelfal) organic C burial record; the Toarcian curve may be a similar proxy. If this is the case, then any anoxic event in the Early Jurassic global ocean post-dated that in the epicontinental seas of Europe. However, it has been argued, for other intervals of geological time, that the principle control on organic C burial rates (the main mechanism of removing light C) is the areal extent of shelf seas (Jenkyns, 1996; Ulicny and others, 1997). It is therefore noteworthy that the positive $\delta^{13}C$ excursion in the early Toarcian shows good correlation with late transgression and highstand (Wignall, 1991).

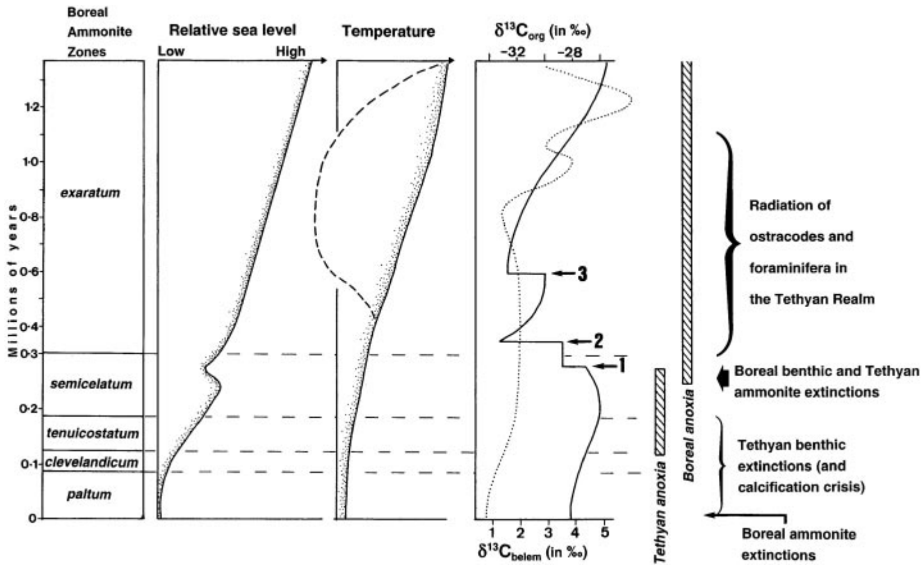

Fig. 7. Summary paleonvironmental history of the early Toarcian (Early Jurassic) interval. The absolute timescale is from McArthur and others (2000), note change of scale at 0.3 myr. Relative sea-level curve is that proposed here. The temperature trends, based on a diversity of data (see text), includes an inferred cooling event (dashed line) in the *exaratum* Subzone based on stomatal index data (McElwain and others, 2005), which is not supported by other data. The organic C isotope trend is from Hesselbo and others (2000), Jenkyns and others (2001) and Kemp and others (2005). The three sharp, negative excursions, labelled 1, 2 and 3, are only seen in the data of Kemp and others (2005) who interpreted them as discrete methane-release events from gas hydrates. The calcite C isotope trend, from belemnites, is from McArthur and others (2000) and van de Schootbrugge and others (2005) and shows little comparison with the organic C data except for a positive trend in the late *exaratum* Subzone. The timing of anoxia and extinctions is based on this work.

PALEOENVIRONMENTAL HISTORY

The detailing of the paleoenvironmental changes in the Cleveland Basins, and their comparison with changes in European Tethyan locations allows a detailed history of change associated with the Toarcian extinction event to be plotted (fig. 7). The Pliensbachian/Toarcian boundary is marked by regression (Wignall, 1991; de Graciansky and others, 1998), a regional extinction event that affected many Tethyan taxa and Boreal ammonites (Little and Benton, 1995; Macchioni and Cecca, 2002; Cecca and Macchioni, 2004), and the culmination of a cooling trend (Bailey and others, 2003; Rosales and others, 2004). The subsequent basal Toarcian transgression coincided with warming, as shown by the northward migration of many warm-water, Tethyan taxa (notably ammonites and brachiopods) into Boreal latitudes (Vörös, 2002; Page, 2004), and by geochemical evidence (Ca/Mg and $\delta^{18}O$ records).

It was during this phase of warming and transgression that the first phase of the Toarcian anoxic event occurred in widespread Tethyan locations. This is generally dated to within the *D. semicelatum* Subzone (Jiménez and others, 1996; Macchioni, 2002; Rosales and others, 2004; Tremolda and others, 2005). Anoxia was not developed in Boreal basins until significantly later, although our new data, showing an earlier mid-*D. semicelatum* Subzone onset of intense anoxia in the Cleveland Basin indicates that there was a brief interval when anoxia was developed throughout the European region. It is significant that the mass extinction of benthos (fig. 3), Tethyan ammonites (Cecca and Macchioni, 2004) and dinoflagellate cysts (Bucefalo Palliani and others, 2002) occurs at this time. This extinction interval occurs during a minor, regional sea-level fall superimposed on the long-term Toarcian rise and suggests there is no link between anoxia initiation and sea-level trends.

A series of sharp, negative $\delta^{13}C$ excursions began at the end of the *D. semicelatum* Subzone (fig. 7) in the North Yorkshire record, and these are postulated to have been caused by the release of vast reservoirs of methane from marine gas hydrate reservoirs (Hesselbo and others, 2000). Modelling suggests that as much as 5000 Gt of C may have been released causing "cataclysmic" environmental change (Beerling and others, 2002, p. 46) and mass extinctions (Kemp and others, 2005). Such claims are likely to be wrong for two reasons. Firstly, as we show here, the excursions occur shortly after the extinctions (fig. 3) and long after the onset of a warming trend (fig. 7). The supposed "cataclysm", recorded in the $\delta^{13}C$ record, actually occurred at a time when many groups were radiating. Secondly, as pointed out above, the excursions occur in black shale facies and are likely to reflect a local signal of stratification within the Cleveland Basin.

The model of gas hydrate release is based mainly on the inferred duration of the negative $\delta^{13}C$ excursions said to be only a few tens of thousands of years in duration (Hesselbo and others, 2000; Kemp and others, 2005). This estimate is based on the claim that 50 μm-thick varves are present in beds 32 to 34 of the Cleveland Basin succession thereby providing a measure of annual sedimentation rates. However, laminations at these levels consist of sharp-based, silt laminae event beds and variably developed, and substantially thicker organic-rich laminae that record a much more aperiodic-style of deposition (for example, fig. 5). Regular, fine-scale varves are not present. Röhl and others (2001) record a similar lack of varves in the equivalent strata of southern Germany. Even laminations forming in modern day settings, such as the Black Sea and the California Borderland where conditions are ideal for the preservation of varves (that is, anoxic conditions and unusually high hemipelagic sedimentation rates), never provide a faithful record due to the frequent development of minor hiatuses (Crusius and Anderson, 1992; Christensen and others, 1994; van Geen and others, 2003).

In summary, the Toarcian paleoenvironmental changes in Europe can be related to a cascade of effects triggered by progressive warming (fig. 7). The relative timing of these effects is controversial, but there is a general consensus as to the ultimate cause of the warming – volcanic CO_2 released from the Karoo-Farrar flood basalt province (see for example, Jenkyns, 1999; Hesselbo and others, 2000; Pálfy and Smith, 2000; Wignall, 2001; Pálfy and others, 2002; Cohen and others, 2004), although Jourdan and others (2005) have cast doubt on even this aspect of the model. The early *D. tenuicostatum* Zone calcification crisis in Tethys may be the first manifestation of this volcanism, with acidification of oceanic surface waters caused by volcanic CO_2 (Mattioli and others, 2004). This may in turn have released further CO_2 into the atmosphere as would warming of surface waters, thereby exacerbating the warming trend (see for example, Kerr, 1998). Interestingly, the development of widespread anoxia and consequent mass extinction may have required only these feedback mechanisms. The role of gas hydrates methane release was either an irrelevant after-effect or may not have happened at all if the $\delta^{13}C$ data is alternatively interpreted.

Models for Anoxia

The recognition that the Toarcian anoxic event in Europe consists of two temporally and spatially separate developments may help resolve the conflicting models for both the cause of anoxia and the associated primary productivity levels.

There is substantial evidence that the Boreal black shales, such as the Jet Rock, were deposited below a stratified water column, in which the surface waters were of somewhat lowered salinity (fig. 8). This includes the abundance of prasinophytes (Prauss and others, 1991), *Tasmanites* (Bucefallo Palliani and others, 2002) and

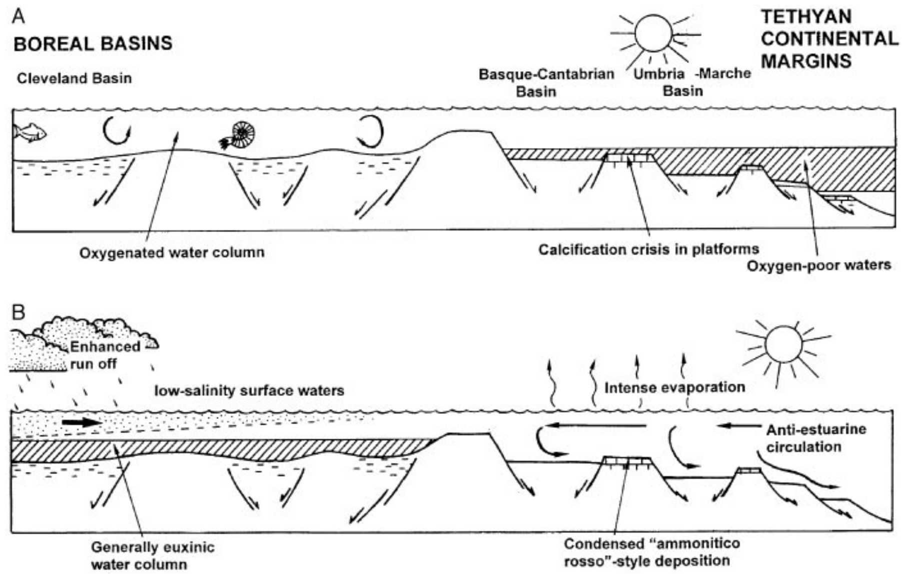

Fig. 8. Cartoon reconstructions of the Boreal to Tethyan transition in western Europe during the early Toarcian. (A) The mid-*tenuicostatum* Zone interval showing development of anoxia on the Tethyan continental margin whilst the Boreal basins remain well oxygenated. (B) The subsequent *exaratum* Subzone Interval showing improvement of ventilation in Tethys, perhaps due to the onset of anti-estuarine circulation in a warming climate, and the development of euxinic conditions in the Boreal basins due to the development of a salinity-stratified water column. The transitional stage between these two scenarios, in the late *semicelatum* Subzone, saw a brief interval when oxygen-poor deposition was at its peak extent. This interval coincides with benthic extinctions.

unusually light $\delta^{18}O$ values from belemnites (Bailey and others, 2003; Rosales and others, 2004). The presence of a salinity-stratified water column may have promoted anoxia due to the restriction of vertical mixing, whereas the trapping of nutrients below the halocline will suppress surface-water productivity (Sælen and others, 2000). However, a lowered salinity during black shale deposition also suggests increased run-off and therefore increased nutrient supply which will stimulate high productivity (Jenkyns, 1999; Cohen and others, 2004); a claim also supported by the $\delta^{15}N$ isotope record (Jenkyns and others, 2001). None of these arguments need apply to the Tethyan black shales because none of the pertinent data comes from this region. Indeed it is hard to envisage how increased run-off could foster increased productivity in these carbonate-dominated sections where the arid hinterlands supplied little or no sediment into the basins.

Evidence for productivity changes associated with Tethyan anoxia comes from the Umbria-Marche Basin and adjacent platform carbonates. Here low abundance, high diversity calcareous nannoplankton and dinocyst assemblages indicate the development of oligotrophic conditions within the *D. tenuicostatum* Zone, probably due to water column stratification (Bucefallo Palliani and others, 1998; Mattioli and Pittet, 2004). However, note that the interpretation of productivity variations from calcareous nannoplankton data can produce conflicting interpretations (Tremolda and others, 2005).

A suppression of upwelling, and a decline of circulation in basins adjacent to the Tethyan Ocean may have been one manifestation of the warming trend at this time (fig. 8). Improvements in ventilation in the latest *D. tenuicostatum* Zone coincided with increased surface-water productivity (Bucefallo Palliani and others, 1998; Mattioli and

Pittet, 2004), probably due to increased vertical advection in non-stratified waters. This improved circulation may relate to the establishment of a strong anti-estuarine circulation in an increasingly warm and arid Tethyan climate. In contrast, in the more northern and humid latitudes the warming trend caused increased run-off and basin stratification.

CONCLUSIONS

Available biostratigraphic dating indicates that the Toarcian anoxic event in Europe is diachronous between Tethyan and Boreal provinces. Anoxia apparently developed and ceased in southern Europe prior to the onset of anoxia in northern Europe. However, detailed investigation of the redox history of the expanded basinal sections of the Cleveland Basin, northern England, indicates that intense anoxia in fact developed somewhat earlier in this region (mid-Bed 31, *D. semicelatum* Subzone) than hitherto recorded. Thus, there was a brief period of overlap in the temporal distribution of black shales throughout the European area. This level coincides precisely with the extinction of most benthic species in the Cleveland Basin and also the extinction of ammonites in Tethys. Thus, the link between the Toarcian mass extinction and widespread marine anoxia is a strong one at least in NW Europe. The new data explain the paradox of the coincidence of faunal recovery and radiation and the supposed peak of anoxia in the *E. exaratum* Subzone. This interval was in fact only characterized by anoxic deposition in the basins of NW Europe whilst newly available, well-oxygenated habitats appeared in southern Europe at this time.

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