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Biotic and stable-isotope characterization of the Toarcian Ocean Anoxic Event through a carbonate-clastic sequence from Somerset, UK

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Abstract: This study focuses on a condensed sequence of alternating carbonate-clastic sediments of the Barrington Member, Beacon Limestone Formation (latest Pliensbachian to early Toarcian) from Somerset (south west England). Abundant ammonites confirm (apart from the absence of the *Clevelandicum* and *Tenuicostatum* ammonite subchronozones) the presence of *Hawskerense* Subchronozone to *Fallaciosum*-*Bingmanni* subchronozones. Well-preserved, sometimes diverse assemblages of ostracods, foraminifera, nannofossils and low diversity dinoflagellate assemblages support the chronostratigraphic framework. Stable-isotope analyses demonstrate the presence of a carbon isotope excursion (CIE), relating to the Toarcian Oceanic Anoxic Event (T-OAE), within the early Toarcian. Faunal, geochemical and sedimentological evidence suggest that deposition largely took place in a relatively deep-water (sub-wave base), mid-outer shelf environment under a well-mixed water column. However, reduced benthic diversity, the presence of weakly-laminated sediments and changes in microplankton assemblage composition within the T-OAE indicates dysoxic, but probably never anoxic, bottom-water conditions during this event. The onset of the CIE coincides with extinction in the nannofossils and benthos, including the disappearance of the ostracod suborder *Metacopina*. Faunal evidence indicates connectivity with the Mediterranean region, not previously recorded for the United Kingdom during the early Toarcian.

Supplementary material: The datasets generated during the current study (Bed-by-bed sedimentology and ammonite occurrences, microfossil range-chart data, $\delta^{13}\text{C}$ stable-isotope data) are available in the University of Birmingham eData repository <https://doi.org/10.25500/edata.bham.00000574>.

The Early Jurassic Toarcian stage (c. 183 to 174 Ma; International Commission on Stratigraphy 2020) witnessed a significant short-lived climatic warming phase, or hyperthermal, which was probably the warmest such event in the Jurassic (Xu *et al.* 2018). This brought about the widespread development of anoxic and euxinic waters in many, but not all, Jurassic oceans (Müller *et al.* 2017, Ramirez & Algeo 2020). Changes were also seen in the pattern of sedimentation across many shelf seas with the deposition of organic-rich shales in some regions that were generally devoid of benthic biota (Danise *et al.* 2013). This event, termed the Toarcian Oceanic Anoxic Event (T-OAE; Jenkyns 1988), referred to by some authors as the 'Jenkyns Event' (Müller *et al.* 2017; Reolid *et al.* 2020), is also associated with enhanced levels of extinction, possibly linked to the multistressors of ocean acidification (Müller *et al.* 2020), climatic warming and anoxia during this time.

The T-OAE is characterised geochemically by a distinct negative carbon-isotope excursion (CIE) through much of the Exaratum ammonite Subchronozone of the early Toarcian, reflecting a marked perturbation in global carbon cycling (Hesselbo *et al.* 2000; Jenkyns 2010). This signal is believed to result from the massive release of isotopically-light carbon into the global ocean-atmosphere system resulting from some combination of volcanic, thermogenic and biogenic sources (Hesselbo *et al.* 2002; McElwain *et al.* 2005). Contemporary activity associated with the Karoo Large Igneous Province is generally considered to be a major contributor to some, or all, of these potential pathways (Greber *et al.* 2020; Sell *et al.* 2014). Geochemical evidence has also shown that the perturbation in the carbon cycle affected both the atmospheric and marine carbon reservoirs (Hesselbo *et al.* 2007; Ruebsam *et al.* 2020) and the impacts can be traced across marine successions irrespective of whether they exhibit dysoxia and black shale deposition. The presence of the CIE across this range of environments makes it a useful stratigraphic marker for the event and allows successions with persistent benthic fauna to be used to document the rates and magnitude of species extinction and turnover.

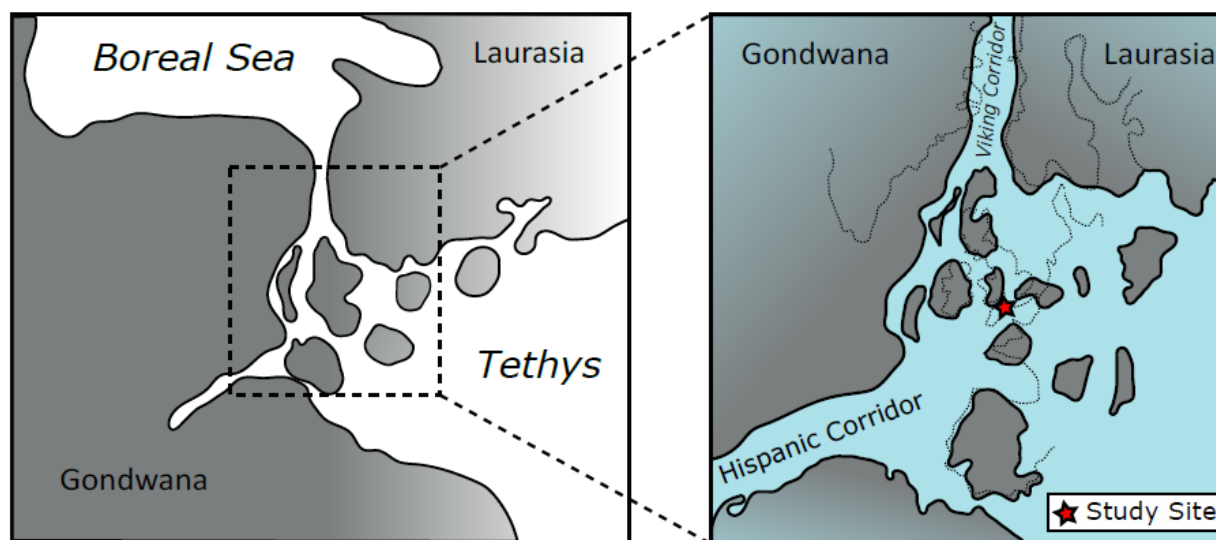


Figure 1. Palaeogeographical setting of south west England in the north west European epicontinental sea (modified after Xu *et al.* 2018). Left panel illustrates the position of north west Europe relative to the northern Boreal and southern Tethyan water. Right panel includes dotted outline of some modern landmasses.

During the Early Jurassic, Britain was situated on the north west margin of the Tethys Ocean (figure 1) at an intermediate position between the cooler, northern waters of the Boreal Ocean and the warmer, southern conditions of the Tethys Ocean (Scotese & Schettino 2017). In Britain, the early Toarcian interval is represented by relatively expanded sections such as the Mochras Borehole (Woodland 1971) and the Yorkshire Coast (Thibault *et al.* 2018), which have become important stratigraphic reference points. However, elsewhere in the UK, this interval is often incomplete, such as the Midlands platform (Caswell & Coe 2012) and/or is highly condensed, for example in the Wessex Basin

(Simms 2004). There are no previous integrated sedimentological, palaeontological and geochemical records through the T-OAE from southern Britain.

The present study focuses on a short section of sediments (< 10 m total thickness) that were exposed during engineering landscape works just north of the village of Seavington St. Michael in south Somerset, south west England (figure 2) in 2009. The original exposure has been further developed and modified in recent years and has been visited and collected by the authors over this period. The original, exposure was first reported by Huxtable (2012) although no measured sections were given. The site is on private land (50°56'17.45" N, 002°50'52.33" W, Great Britain Ordnance Survey Grid ST 40521 15757) near to the Hurcott Lane Cutting mentioned by Simms (2004, p.94) and about 1 km north west of the 'Ilminster' sections studied by Boomer (1992) and Boomer *et al.* (2009), the town of Ilminster lies just 4 km to the west.

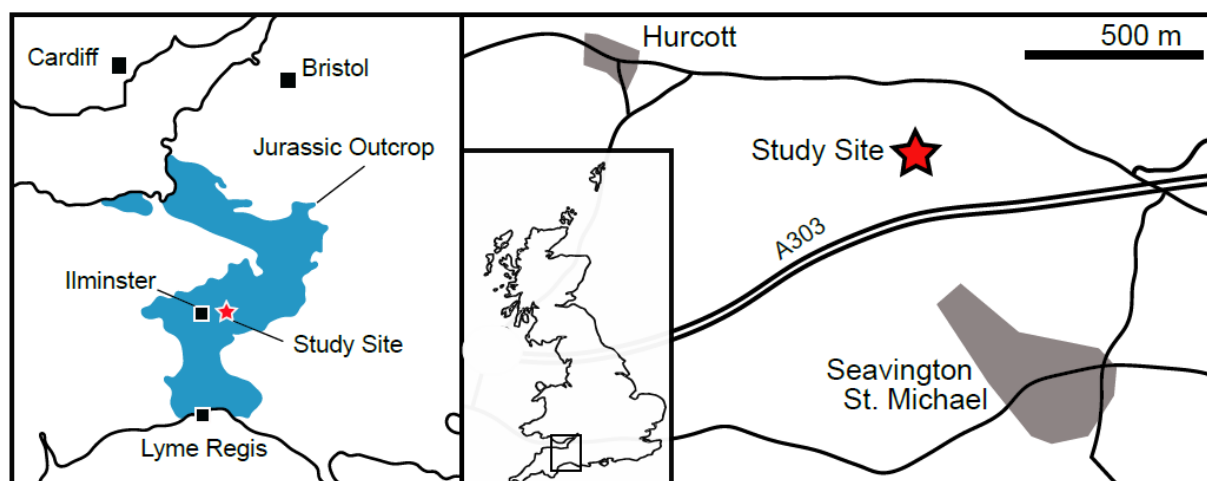


Figure 2. General location map showing the position of the study site in relation to the distribution of Early Jurassic sediments in south west England (left panel) and a more detailed local map (right panel).

The section provides a largely continuous exposure from the top of the Pliensbachian through to the mid-late Toarcian except for the *Tenuicostatum* Chronozone, much of which is highly condensed and/or eroded, at least in part. Although this entire section is clearly condensed (the same interval in the Mochras Borehole is represented by more than 200 m of sediments) the abundance and diversity of both ammonites and many of the microfossil groups throughout the section has allowed a robust chronostratigraphy to be established together with providing insights into faunal provinciality and changing palaeoenvironmental conditions during this important period in earth history.

Early Jurassic sediments from this area have been reported previously, however, many of those localities were either temporary (e.g., the Ilminster A303 bypass; Boomer 1992; Prudden & Simms 2014; Boomer *et al.* 2009) or have subsequently been covered over (e.g., the Strawberry Bank Quarry, Moore 1853; 1866). Simms (2004) provided a detailed description of an exposure referred to as the Hurcott Lane Cutting (based on Constable 1992, an unpublished MSc thesis). The present study is based on a section just north of Seavington St Michael (referred to hereafter as Seavington), that was discussed by Huxtable (2012) in his review of the ammonite faunas of the Beacon Limestone Member and Marlstone Rock Bed in the area. Huxtable (*Ibid.*) noted the abundance of ammonite faunas in these beds and highlighted their stratigraphic importance.

None of these previous works reported evidence for dysoxic conditions, as might be expected during the T-OAE. However, Williams *et al.* (2015) noted that the exceptionally preserved vertebrate and insect fauna of the nearby Strawberry Bank Lagerstätte, were preserved in a series of nodules from an interval immediately after the peak of the biotic crisis associated with the T-OAE. The fauna was originally recorded by Moore (1853) from a quarry in the nearby town of Ilminster, but the material was not studied in detail until much later. Williams *et al.* (2015) interpreted the Strawberry Bank

sediments as representing relatively shallow marine environments, the vertebrate fossils being dominated by immature forms that would have favoured sheltered conditions, the sediments also lacked the relatively more open water indicators such as belemnites and ammonites in any great number. There is no evidence for the development of this Lagerstätte association in the Seavington section described here.

Lithostratigraphy and sedimentology

On the Dorset coast (Wessex Basin) the latest Pliensbachian to late Toarcian interval is represented by a condensed unit of well-cemented carbonates, less than 10 m thick, referred to the Beacon Limestone Formation (Cox *et al.* 1999). The Beacon Limestone Formation was subdivided by Cox *et al.* (1999) into an upper Eype Mouth Limestone Member and a lower Marlstone Rock Member, although neither of these members are formally defined at present (British Geological Survey 2020). Cox *et al.* (1999) considered this scheme to apply to south Somerset also, however, the Beacon Limestone Formation in this area is significantly different in lithology from the Dorset coast succession to warrant assignment to the Barrington Member, which has been formally described (British Geological Survey 2020). Furthermore, most workers regard the Marlstone Rock as having formation status, rather than a member, which is the approach followed herein. The lithostratigraphic framework for this study is shown in figure 3 with the standard scheme for the Dorset Coast part of the Wessex Basin provided for comparison. For an overview of the Beacon Limestone Formation lithostratigraphy in south Somerset and the Dorset Coast see Huxtable (2012, figure 1 therein).

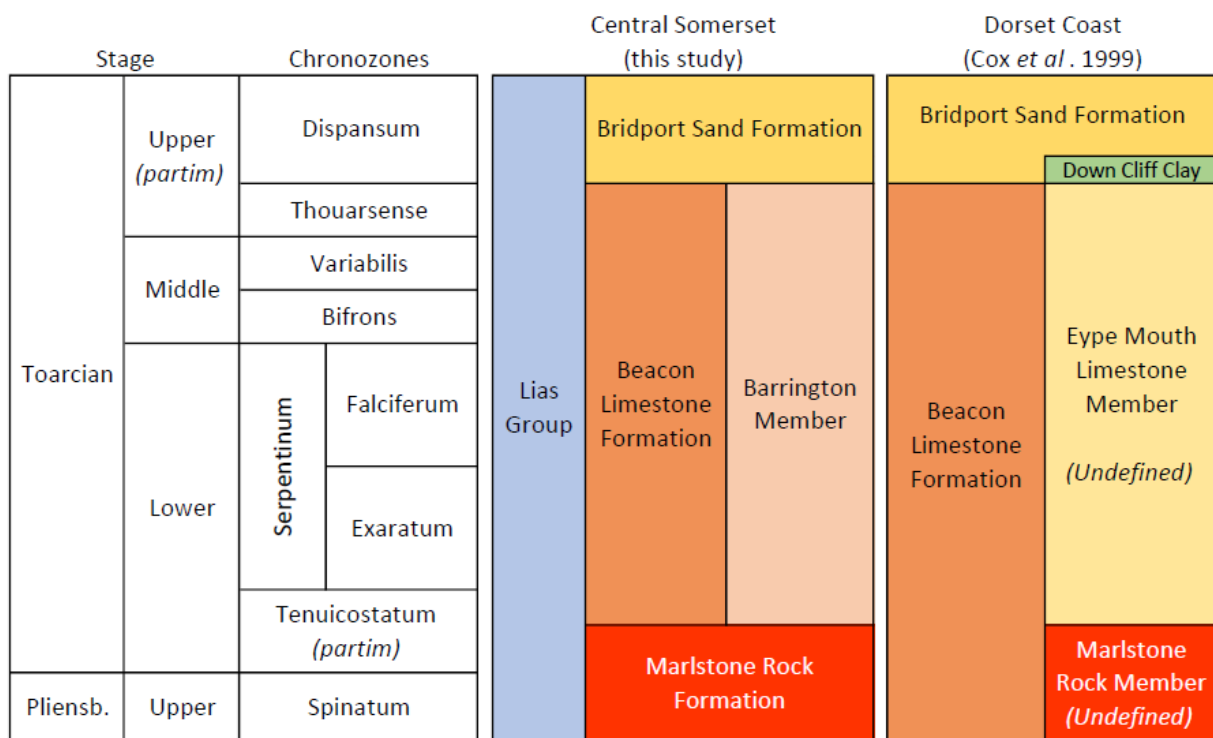


Figure 3. Chronostratigraphy (left) and lithostratigraphy (centre) for the Late Pliensbachian and Toarcian sediments of south Somerset. The equivalent lithostratigraphic scheme for the Dorset Coast (Wessex Basin, after Cox *et al.* 1999) is shown on the right.

The sediments at Seavington (figure 4A-C) and those described from the local area, consist of a basal, well-cemented, ferruginous sandstone belonging to the Marlstone Rock Formation overlain by a series of well-bedded (decimetric-scale) nodular to massive limestones separated by more clastic-dominated, friable, calcareous siltstones. These clastic-carbonate alternations are assigned to the Barrington Member of the Beacon Limestone Formation and include clear sedimentological evidence for a local expression of the T-OAE, including dark, weakly laminated sediments with wood preserved

(Bed SM4d and Bed SM5). The sediments at Seavington provide the first evidence for the T-OAE in south west England.

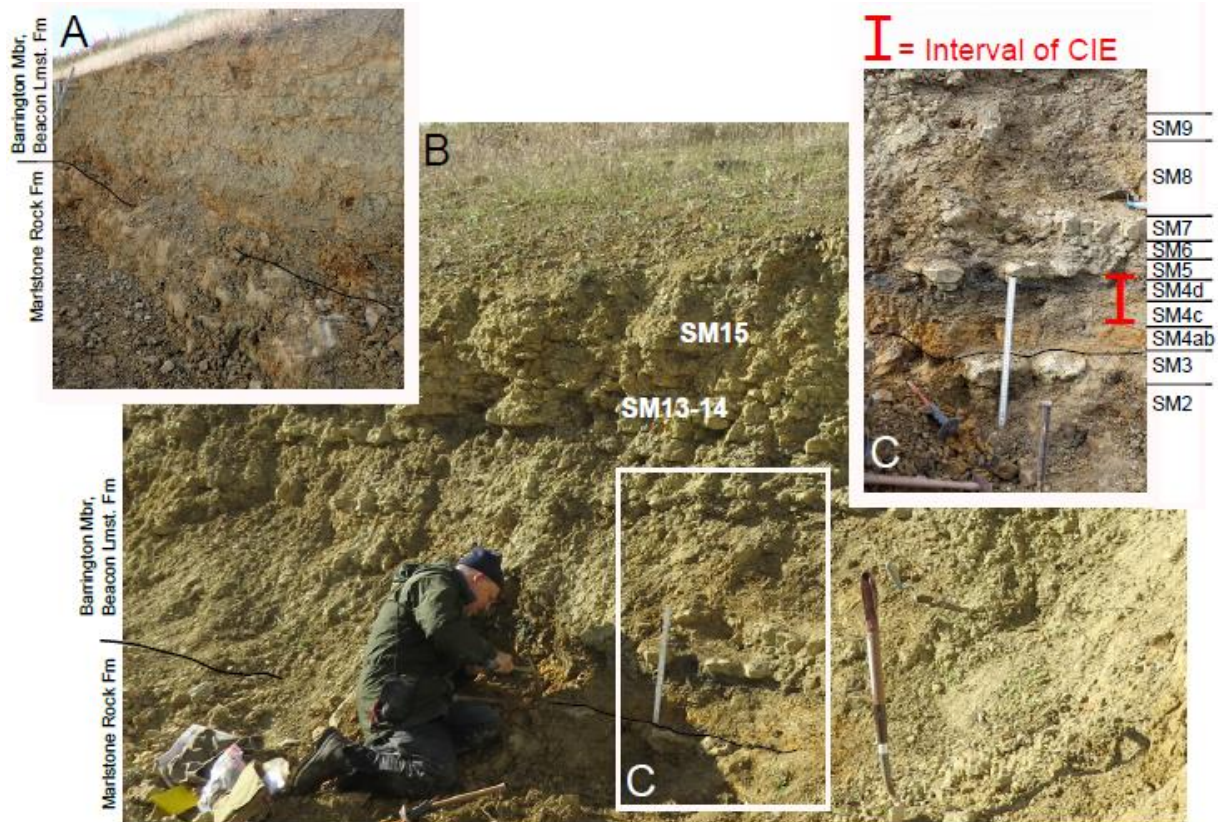


Figure 4. Upper Pliensbachian-Toarcian boundary interval exposed at Seavington, Somerset, showing Marlstone Rock Formation overlain by alternating nodular limestone and claystone unit containing dark claystone, with carbon isotope excursion. A. Irregular and poorly defined contact between Marlstone Rock Fm and Beacon Limestone Fm. B. Main photograph illustrates typical exposure and lithological variability, C. Detail of box on figure 4B showing earliest Toarcian beds. Black line across figures marks the boundary between the Marlstone Rock Fm and the Beacon Limestone Fm. White scale bar in 4B and 4C is 50 cm. (Photos: P. Copestake, K. Page).

In total, 34 separate beds (designated SM1-SM34) were recorded during detailed investigation of the site over several visits, and their stratigraphical distribution is illustrated in figure 5. The basal units (Beds SM1-SM3) comprise the Marlstone Rock Formation, while all the younger beds are assigned to the Barrington Member of the Beacon Limestone Formation. It is not the intention to provide a detailed bed-by-bed description here, since the section has previously been discussed (Huxtable 2012) but a summary, with additional comments and observations for important intervals, are provided below, with further details in the supplementary material.

Marlstone Rock Formation

The Marlstone Rock Formation is considered to be geographically limited to the Worcester Basin and East Midlands Platform (British Geological Survey 2020), however, the sedimentological, biostratigraphical and chronostratigraphic assessment of the basal unit in the present (SM1) and previous studies in the area, e.g., Ilminster (Boomer *et al.* 2009), clearly indicate that the formation can be recognised into south Somerset.

The Marlstone Rock Formation, Beds SM1-SM3 at this locality, comprises a carbonate/iron-cemented, orange to light brown coloured, quartz-oid sandstone that displays large specimens of pectinid bivalves, belemnites and ammonites with occasional brachiopods, on its uppermost surface. The unit

weathers to a distinctive dark orange-brown but has not been examined in any further detail in the current study. The age of Bed SM1 is determined as Spinatum Chronozone by the ammonite occurrences observed on the exposed surfaces, details provided in relevant section below.

Barrington Member, Beacon Limestone Formation

The sediments of the Barrington Member (Beds SM4 to SM34, this work) comprise a series of laterally continuous, well-bedded, nodular to massive limestones and friable siltstones that dip at about 2-4° to the southeast. The BGS records this unit as being present in the Wessex Basin, the Central Somerset Basin and Mendips-Radstock Shelf area to the north, noting a thickness of up to 5 m but typically less than 1.5 m. In the present study the beds reach a total of just over 4 m although the contact with the overlying Bridport Sand Formation was not observed at Seavington. Boomer (1992) recorded a total thickness of closer to 9 m in total for this unit in the nearby Ilminster sections where it was seen to meet the Bridport Sand Formation.

Within the Barrington Member, lithologies switch between early-cemented limestones and poorly to non-cemented, friable siltstones. The nodular limestone beds are more obvious at exposure and markedly nodular in the lower part of the section (e.g., beds SM4, SM6), passing up into more massive limestones. All beds contain abundant micrite-filled ammonites (with occasional sparry calcite infill) as three-dimensional fossils suggesting early diagenesis throughout this unit. However, aragonite preservation has not been recorded and most of the ammonites are preserved as relatively complete, internal steinkerns. Well-preserved belemnites are also common, particularly at certain levels, while bivalves, ophiuroid and echinoid fragments and small brachiopods are present but not common. No other macroinvertebrates have so far been recorded in any great abundance. Trace fossils are observed occasionally but they are not a common feature. No vertebrate remains have been encountered and none of the nodules examined yielded the exceptional preservation that is characteristic of the nearby Strawberry Bank Lagerstätte.

Calcareous microfossils are generally well-preserved but again, no aragonitic microfossils have been encountered, although they are known elsewhere in sediments of this age. This could point to the early loss of aragonitic carbonate from ammonites and other aragonite-secreting organisms soon after burial which may well have acted as a source for the carbonate cement. However, there is no evidence to suggest that aragonitic microfossils had been present (e.g., steinkerns). It is not clear why some layers should have been preferentially cemented but it is likely that differences in the grain-size of the original sediment may have influenced this process.

The greatest sedimentological variability in the section occurs in the lowest metre. The lowermost bed (Bed SM1, even numbered beds are generally the friable, clastic units, odd numbers are mainly cemented carbonates) is a well-cemented unit and constitutes the bulk of the Marlstone Rock Formation at this site (figure 4A). Bed SM2 is a sandy siltstone with an abundance of belemnites lying on the upper surface of Bed SM1, it may represent a winnowed, reworked deposit, possibly the result of sea-level fall associated with global cooling in the very latest Pliensbachian (Partington *et al.* 1993; van de Schootbrugge *et al.* 2005). This event was responsible for a major hiatus across the European epicontinental sea region (Morard *et al.* 2003). Bed SM2 fills depressions of up to 30-40 cm in the underlying SM1. The lowermost nodular units in this study (Beds SM3 and SM5) are clearly diagenetic in origin as they are laterally discontinuous and distort sediments above and below them (figure 4B, 4C).

The next youngest clastic unit (Bed SM4) has a distinct, laterally continuous, orange-brown appearance in the lower half (see figure 4C), changing upwards to a medium-dark grey, eventually becoming almost black with weak laminations at the top which continues into the voids between the nodules of Bed SM5. The colour then lightens above SM5, returning to a medium grey-brown (i.e. into Bed SM6) that is characteristic of most clastic beds at Seavington. The origin of the distinctive orange layer is unclear but may relate to recent hydrogeological alteration of iron. The biostratigraphic and

geochemical evidence discussed below clearly indicates that the dark, laminated clastic unit from mid-Bed SM4 to the base of Bed SM6 represent the T-OAE at this site, this is confirmed by the presence of a carbon isotope excursion (CIE) through these beds (see below). The distribution of the remaining overlying sedimentary units can be seen in figure 5.

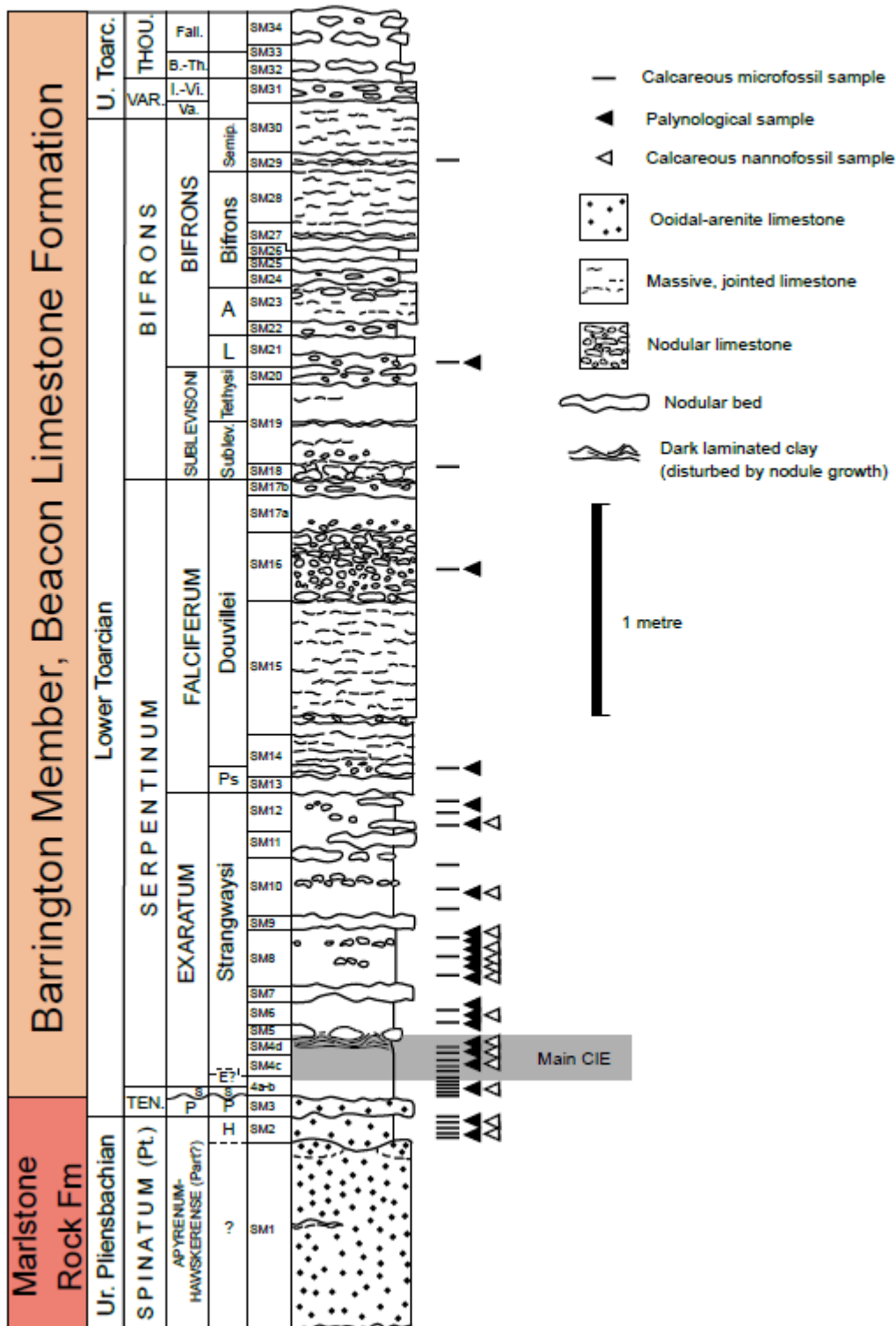


Figure 5. Summary lithological log of the exposure near Seavington St Michael, south Somerset, showing chronostratigraphy, lithostratigraphy, ammonite chronostratigraphy, bed numbers and micropalaeontological sample points.

Ammonoid biostratigraphy and assemblage composition (KNP)

The Toarcian 'Junction Bed', or Barrington Member, of the Ilminster district has long been known as a rich source of ammonoid fossils, with species such as *Ammonites elegans*, now *Cleviceras elegans*, first being described as long ago as 1815 by J. Sowerby, and detailed studies being published by the local priest, the Reverend Charles Moore in 1866. It was not until the early twentieth century, however, that the rich faunas began to be more systematically studied by the high-resolution ammonoid chronology pioneer, S.S. Buckman (see Page 2017) when new sections were created during new quarrying activities and reservoir construction between Barrington and Stocklinch, as described by Hamlet (1922), Pringle & Templeton (1922) (later reviewed by Howarth 1992).

Revision of this early work has been hindered, however, as exposures in the soft limestone-marl sequence rapidly degrade and become overgrown, and the only quasi-permanent exposure in the sides of Hollow Lane, north of Hurcott Cross and north west of Seavington St Michael (Wilson *et al.* 1958), lacks the lowest part of the succession (Simms 2004, based on the unpublished MSc thesis of Constable 1992). The section is partially overgrown, however, and very difficult to systematically sample safely to update these basic records (Page 2020). The construction of the A303 Ilminster bypass in 1987, however, allowed more systematic sampling of the entire Barrington Member (Boomer *et al.* 2009), although the nature of the construction works, with short-lived and incomplete sections left many open questions regarding the ammonite sequence. The bypass sections are no longer exposed.

Excavations at the Seavington processing site commenced in 2009 with a general collection of ammonoids provided by JH to the Natural History Museum London and a description published by Huxtable (2012). Suitable sections that allowed a fresh approach to systematic sampling of the ammonoid fauna subsequently became available because of further site development, with an estimated > 3000 ammonites having been recovered so far and analysed by KNP. This collection forms the basis of the current study.

Biogeographical affinities and correlation

The ammonoid fauna of the Lower Toarcian in the section is overwhelmingly of Submediterranean Province type being dominated by Hildoceratidae and Harpoceratidae, and strongly contrasts with that of the North Yorkshire coast which is typically dominated by Dactyloceratidae, and hence with Subboreal affinities (Page 2003; 2004; 2008). As a result, the Subboreal, Standard Chronozonal scheme as developed for the North Yorkshire coast and typically applied in the UK (e.g., Howarth 1992), is not applicable to the Submediterranean ammonoid faunas of southern England and hence the more appropriate French scheme of Elmi *et al.* (1997) has been applied (Page 2003; 2004). To facilitate comparison with the Subboreal sequences of Yorkshire, however, correlations with the biohorizons described by Page (2004) may be made, as indicated below.

In contrast, the underlying upper Pliensbachian, developed in Marlstone Rock Formation facies does contain a typical Subboreal fauna dominated by a *Pleuroceras* (Amaltheiidae) dominated fauna and hence the same chronozonal scheme can be applied as elsewhere in the UK, including North Yorkshire (although refined using sub-subchronozonal 'Horizons' as reviewed by Dommergues *et al.* 1997). In addition, although the lowest upper Toarcian, as developed in the uppermost part of the Barrington Member, can also be correlated with the same ammonoid chronozonation for the substage as the rest of the UK - now for the North West European Province - the scheme of Dean *et al.* (1961) as used by Howarth (1992) has been superseded, and that of Elmi *et al.* (1997) is used here. The terminology and concept of chronozones, subchronozones, sub-chronozonal 'Horizons', and successive faunal 'events' used to correlate 'Biohorizons' herein, is comprehensively reviewed by Page (2017).

Crucially, the abundance of ammonites throughout the section, has facilitated the recovery of faunas from over 55 successive levels across 34 beds, with many rare forms now being recorded in position for the first time in the region, thereby providing opportunities for correlations beyond Europe. In

addition, several evolutionary lineages are demonstrated in the studied section in more detail than elsewhere in the UK and probably beyond, most notably the sequence of over 10 species of the *Harpoceratoides-Harpoceras* lineage (Harpoceratidae) and 13 species of the *Hildaites-Hildoceras* lineage (Hildoceratidae) (the latter including the classic sequence of *Hildoceras* species described by Gabilly 1976).

Although the Dactyloceratidae are common at some levels, they are very rare at others and, due to the large number of available species and generic names thanks to Buckman (1909-1930) and others, including Gabilly *et al.* (1971), it would be premature to attempt to state how many distinguishable species are truly present in the new section. Although taxonomic discussions and conclusions will be published elsewhere, correlations with current chronostratigraphic frameworks across Europe are nevertheless quite clear and these are discussed below.

It should be noted that although Howarth (1992) established the Barrington section as a 'standard' or reference succession for the Barrington Member of the area, every known section in the unit across the site is different in terms of bed sequence and biochronological record and, furthermore, major changes in thickness are also evident (see Wilson *et al.* 1958 for instance). Hence, any attempt to comprehensively apply the bed numbering system for Barrington to any other section is simply not tenable, even if certain beds may still apparently be recognisable, or at least correlatable, based on combined lithological and faunal characters. However, to enable comparisons, general correlations between the new Seavington sections and both Howarth's (1992) record of the Barrington section and the composite section of Boomer *et al.* (2009) from the A303 road cutting (temporary section, no longer exposed) are included in the chronostratigraphic descriptions below, where appropriate. The succession of ammonite chronostratigraphic zones in the section at Seavington is described below, in ascending order.

Upper Pliensbachian Ammonite Stratigraphy

Spinatum Chronozone (Beds SM1-SM2).

Hawskerense Subchronozone, Hawskerense Horizon (Index: *Pleuroceras hawskerense* (Young & Bird)).

Although only an upper unit of the Marlstone Rock Formation appears to have been exposed during site operations (i.e., Beds SM1-SM3), specimens of *Pleuroceras* sp. *hawskerense* from the ferruginous sandy silts of Bed SM2 indicate that at least this part of the sequence includes material of Hawskerense Subchronozone and Horizon age, hence marking the top of the Pliensbachian Stage. Several specimens of the inner whorls of macroconchs, comparable to *P. spinatum* (Bruguière) *sensu* Howarth (1958) have been recovered from the top surface of Bed SM1 and appear to be within intraclasts. In the absence of any additional confirmed records from this level, or determinable specimens from lower in SM1, subchronostratigraphic and horizonal assignment is currently not possible. Comparison with the Ilminster bypass (Boomer *et al.* 2009), however, suggest that it is possible that Bed SM1 may include the preceding Apyrenum Subchronozone up to around 25 cm below its top, based on the presence of *P. solare* (Phillips) at that location (Page in Boomer *et al.* 2009, p.82), although this cannot be confirmed at the Seavington site.

Lower Toarcian Ammonite Stratigraphy

Tenuicostatum Chronozone (Bed SM3).

Paltum Subchronozone, Paltum Horizon (Index: *Protogrammoceras paltum* (Buckman)).

Dactyloceras (*Eodactylites*) cf. *pseudocommune* Fucini on the top surface of Bed SM3, and compatible nuclei within the Bed, indicates the basal Toarcian, Paltum Subchronozone and Horizon of the *Tenuicostatum* Chronozone. The apparent absence of the index *Protogrammoceras paltum* in Bed SM3, which is both common and typical of the Subchronozone on the Dorset coast, and, to a lesser extent on the North Yorkshire coast (Howarth 1992), may suggest a slight difference in age. A

fragment of *Pleuroceras* cf. grp *hawskerense* in the lower part of Bed SM3 is clearly derived from earlier levels.

The *Eodactylites* fauna has not been recorded at Barrington or from the A303 sections, with the oldest Toarcian fauna at the former being *D. (Orthodactylites) cf. tenuicostatum* (Young & Bird) in Bed 1, apparently associated with *Pleuroceras* spp., and at the latter, probable 'fine ribbed' *Orthodactylites* on the base of Bed 3.

Tenuicostatum Chronozone (Bed SM4a).

Semicelatum Subchronozone, Semicelatum Horizon (Index: *Dactylioceras (Orthodactylites) grp semicelatum* (Simpson)).

The basal 2-3 cm of Bed SM4 (i.e., Bed SM4a) locally yields crushed and fragmented *Dactylioceras (Orthodactylites) grp semicelatum*, the close primary ribbing of which contrasts with the more widely spaced primary ribbing of earlier *Eodactylites* (which, as the identified species name suggests, more closely resembles the less dense ribbing of later, Bifrons Chronozone *Dactylioceras commune* (J. Sowerby)). As *O. semicelatum* indicates the Semicelatum Horizon at the top of the Tenuicostatum Chronozone, a non-sequence must exist between the top of Bed SM3 and the base of Bed SM4, which omits the intervening Crosbeyi and Tenuicostatum subchronozones of the Tenuicostatum Chronozone. In the apparent absence of *Tiltoniceras antiquum* (Wright), assignment to either the To5 (*semicelatum*) or To6 (*antiquum*) biohorizons of Page (2004) is not yet possible. *D. (O.) grp semicelatum* in Bed 2 at Barrington indicates that correlation is possible at horizon level, and *T. cf. antiquum* from the A303 roadworks confirms that To6 is present in the area.

Serpentinum Chronozone (Bed SM4b).

Exaratum Subchronozone, ?Elegantulum Horizon (Index: *Elegantuliceras elegantulum* (Young & Bird)) (Note that the use of *Cleviceras exaratum* (Young & Bird) as a subzonal index for this interval by Buckman (1910) has priority over the use of *E. elegantulum* by Gabilly (1976)).

Although Bed SM4b is virtually barren of recognisable fossils due to intensive iron oxide alteration, a small number of fragmentary specimens have been recovered include a crushed shell with a resemblance to *Elegantuliceras*. If this determination can be confirmed by additional finds, then it may be only the second first record of the genus, and hence the Elegantulum Horizon and the To8 (*elegantulum*) Biohorizon in Britain south of the North Yorkshire coast (see Howarth 1992) - the only other (unpublished) record being from the Hill Lane borehole at Brent Knoll, West Somerset (*per. obs.*, British Geological Survey BDD4948; see also Martin 2013). The only other ammonite recorded from a similar level in the new section is a fragment of *Harpoceras (Harpoceratoides) sp.* with limestone infill and there is no evidence of the Elegantulum Horizon at Barrington or in the A303 sections.

Serpentinum Chronozone (Beds SM4c-SM12).

Exaratum Subchronozone, Strangewaysi Horizon (Index: *Harpoceras (Harpoceratoides) strangewaysi* (Sowerby)).

The incoming of abundant of *Harpoceras (Harpoceratoides)* in Bed SM4c would indicate the base of the Strangewaysi Horizon of Elmi et al. (1997). Although all specimens are crushed in SM4c and SM6a, uncrushed shells in SM5 confirm that the form present is more evolute than typical *H. (Harpoceratoides) serpentinum* (Schlotheim) *sensu stricto* and closely comparable to *Harpoceras (Harpoceratoides) kisslingi* Hug (as figured by Gabilly 1976, pl. 4, figs 5, 6). The presence of occasional *Cleviceras exaratum* throughout this interval places it within the To8 (*exaratum*) Biohorizon of Page (2004). Rare *Hildaites grp levisoni* (Simpson) – *murleyi* (Moxon) (as figured by Howarth 1992) is also present in SM4c and SM5 above. *Dactylioceras* and *Nodicoeloceras* are also present.

From Bed SM6b to about the basal 5 cm of the overlying Bed SM8a, *H. (Harpoceratoides) grp serpentinum* is common, including specimens close to the holotype of *Harpoceras (Harpoceratoides) alternans* (Simpson) (see Howarth 1992, pl.16, figs 1a, b) and macroconchs close to the Northamptonshire specimen figured by Howarth (*Ibid.* text-fig. 26). Occasional *Dactylioceras (Orthodactylioceras) semiannulatum* Howarth, *Nodicoeloceras* and rare *Hildaites* are also present in this interval, with rare *Cleviceras grp elegans* (J. Sowerby) indicating that Bed SM7 belongs to the To9 (*elegans*) Biohorizon (the species group – and hence the Biohorizon – however, persisting to at least Bed SM10b, placing a provisional upper limit to the Biohorizon). *H. (Harpoceratoides) grp serpentinum* is recorded to near the top of Bed 12b - although later Strangewaysi Horizon faunas become dominated by Dactylioceratidae - and are replaced in Bed 13, by *Harpoceras (H.) pseudoserpentinum* Gabilly marking the top of the Horizon and base of the succeeding Pseudoserpentinum Horizon and Falciferum Subchronozone.

Throughout this interval, from beds SM6a to SM12b, changes in both *Harpoceratoides* and *Dactylioceras* faunas, and potentially within the *C. elegans* group, indicate that the *elegans* Biohorizon may ultimately be subdivisible. For instance, specimens of *Harpoceratoides* from the upper part of Bed SM12, show transitional characters to *H. pseudoserpentinum*, a change also noted by Howarth (1992) near the top of the Exaratum Subchronozone at Barrington (e.g., Pl. 17, figs 1a, b, 2a, b).

Beds equivalent to SM7 appear to be widely recognisable in the region based on the distinctive fauna, including at Barrington (Bed 6, e.g., Howarth 1992, pl. 16, figs 5a, b), at Strawberry Bank (Ilminster; *pers. obs.*; locality described by Williams *et al.* 2015) and in the A303 roadworks sections as Bed 8 of Boomer *et al.* (2009). Higher levels at all three other sites, however, do not correlate well, emphasising that using the Barrington section of Howarth (1992) as a standard for the area does not work.

Serpentinum Chronozone (Beds SM13 and lower part SM14).

Falciferum Subchronozone, Pseudoserpentinum Horizon (Index: *Harpoceras (Harpoceras) pseudoserpentinum*) (= *pseudoserpentinum*) Biohorizon (To10).

Bed SM13 and the basal 3 cm or so of Bed SM14 yield a distinctive assemblage not previously confirmed in the UK and is characterised by *Harpoceras (Harpoceras) pseudoserpentinum*. The species is well illustrated by Gabilly (1976, pl. 6, figs 1, 2, pl. 7, figs 1, 4, 5, pl. 8, fig. 1, pl. 9, figs 1, 2) and shows features intermediate between *Harpoceras (Harpoceratoides) grp serpentinum* and *Harpoceras (Harpoceras) falciferum* (Sowerby). Associated with this are abundant dactylioceratids especially distinctive stout-whorled forms identical to *Nodicoeloceras crassoides* (Simpson) *sensu* Howarth (1978, pl. 3, fig. 1 only, i.e., the lectotype of *Ammonites annulatus* J. Sowerby) as well as *Dactylioceras* sp. Occasional *Hildaites cf. serpentiniformis* Buckman (comparable to Howarth 1992, pl. 32, 5a, b, pl.33, figs 3a, b) and rare *Polyplectus (Praepolyplectus) aff. pleuricosta* (Haas), the latter at a much lower level than previously record by Howarth.

This distinctive fauna has also now been recorded at the Strawberry Bank locality near Ilminster (*per. obs.* 2019), but was not recorded in the A303 roadworks sections by Page *in* Boomer *et al.* (2009) or at Barrington by Howarth (1992), hence the base of the Falciferum Subchronozone may not yet be precisely located at either of the latter sites (but would lie between beds 10 and 13 at the former and between beds 12 and 17 at the latter, although the record of “*N. crassoides*” in Bed 16 may indeed indicate the Pseudoserpentinum Horizon).

Serpentinum Chronozone (Upper part Bed SM14-Bed 17b).

Falciferum Subchronozone, Douvillei Horizon (Index: *Hildoceras (Orthildaites) douvillei* (Haug)).

The use of *Orthildaites douvillei* as an index for this interval has never been satisfactory, not least in that it is usually rather rare, whereas the most abundant faunal element is typically *Harpoceras (Harpoceras) grp falciferum*. However, as many authors (including Elmi *et al.* 1997) believed that the

latter species persisted into the overlying Bifrons Chronozone, it was considered unsuitable as an index. New information from the Seavington St. Michael section, however, indicates that *H. grp faciferum*, appears immediately above *H. pseudoserpentinum* at around 4-5 cm above the base of Bed SM14, and persists until replaced by the stouter-whorled and stronger-ribbed *H. (H.) falciferoides* Buckman *sensu* Gabilly (1976) at around 10 cm below the top of Bed SM16 – hence its range is indeed restricted to the upper part of the Falciferum Subchronozone.

Large specimens of *H. (H.) falciferoides sensu* Gabilly are common at the top of Bed SM17a and in SM17b and the species persists well into the Bifrons Chronozone above. Typical examples figured by Gabilly are also from these later levels (including pl.13, figs 1,2, pl.14, fig. 1, 2, pl.16. figs 1, 2) and a very large specimen, 342 mm in diameter, from a similar level in Northamptonshire is figured by Howarth (1992, text fig. 32) under the name '*H. falciferum*'. In contrast, *H. (H.) falciferum sensu stricto* is a smaller form, macroconchs typically up to around 200 mm diameter, with less projected falcoid ribbing (typical specimens figured by Howarth 1992 include pl. 19, figs 3a, b, pl. 20, figs 5a, b and text fig. 30, including the holotype of *Harpoceras mulgravium* (Young and Bird)). Associated with *H. (H.) falciferum* s.s. are common *Dactylioceras* sp. and less frequent *Nodicoeloceras* sp., with occasional *Hildaites*, including rare *Hildaites* aff. *serpentiniformis* near the base of the Horizon (SM14). Also noted were frequent forms referred to '*Hildoceras lusitanicum* (Meister)', as figured by Howarth (1992), pl. 36, figs 1a, b, 2a, b only) in the lower part of Bed SM15. Very rare *Polyplectus* (*Praepolyplectus*) aff. *pleuricosta* are also present.

The higher part of the Horizon, with *H. (H.) falciferoides sensu* Gabilly, also yields *Dactylioceras* sp. and *Nodicoeloceras* sp. with frequent *Orthildaites* grp *douvillei*, including specimens identical to those figured by Gabilly (1976, e.g., pl.19, figs 8-13, pl.20, figs 3-5) from Anse St. Nicholas, Vendée, western France. The changes in *Harpoceras* faunas, as well as the restriction of *Orthildaites* to the top of the original Douvillei Horizon indicates that it may potentially be subdivided. The To11 (*falciferum*) Biohorizon of Page (2004), therefore, would only correspond to the interval within which the index occurs, from around 5 cm above the base of SM14 to 10cm below the top of SM16.

The Douvillei Horizon probably corresponds to the interval from Bed 13 to the lower part of 16 (based on lithological characters) in the A303 sections of Page in Boomer et al. (2009) and beds 17 to 23 at Barrington (Howarth 1992).

Bifrons Chronozone (Bed SM18 and lower half SM19).

Sublevisoni Subchronozone, Sublevisoni Horizon (Index: *Hildoceras (H.) sublevisoni* = *Hi. laticosta* in Howarth 1992).

The incoming of abundant *H. grp sublevisoni* in Bed 18 marks the base of the Bifrons Subchronozone, and the Sublevisoni Subchronozone and Horizon. The species is figured by Gabilly (1976, including pl. 22, figs 1, 2 and pl. 22, figs 5, 6 as '*Hi. caterinii* Merla') and Howarth (1992, pl. 34, figs 4a, b, 5 and ?6 as *Hi. laticosta*). Occasional *H. falciferoides sensu* Gabilly are also present and common *Dactylioceras* and *Nodicoeloceras*. Crucially a single *Ovaticeras ovatum* (Young and Bird) has been recovered, confirming a correlation with the To12 (*ovatum*) Biohorizon of Page (2004) (a specimen from the adjacent A303 sections has been figured by Howarth (1992), pl. 23, figs 4a, b – see also Page in Boomer et al. 2009). *H. grp sublevisoni* persists into Bed SM 19a where dactylioceratids include *D. (D.) commune* and *Nodicoeloceras*, the former indicating the To13 (*commune*) Biohorizon. *Harpoceras (H.) grp falciferoides sensu* Gabilly is also present at this level.

This horizon probably corresponds to the lower part of Bed 18 of Page in Boomer et al. (2009) in the A303 sections and to Bed 18 at Barrington, from which a typical fragment of *H. sublevisoni* is figured by Howarth (1992, pl. 34, fig.6).

Bifrons Chronozone (Upper half Bed SM19 and SM20).

Sublevisoni Subchronozone, Tethysi Horizon (Index: *Hildoceras (H.) tethysi* (Geczy)).

H. tethysi first appears in Bed SM19b, marking the base of the Horizon, and persists to the basal surface of Bed SM20b (the species is described and figured by Gabilly 1976, including pl. 21, figs 1-4, pl. 23, figs 6, 7, pl. 29, figs 3-6 and pl. 23, figs 3-5 as '*H. crassum* Mitzopoulos'). Associated with it are occasional *H. falciferoides sensu* Gabilly, *Dactylioceras* spp. and *Nodicoeloceras* sp. The presence of *Dactylioceras (D.) grp athleticum* (Simpson) in the upper part of the Horizon (from Bed SM20a) indicates the To14 (*athleticum*) Biohorizon of Page (2004), which persists through the succeeding Lusitanicum and into the lowest Apertum horizons (see below), hence an indication that subdivision is also possible here.

Howarth's figure of a probable *H. tethysi* from Bed 25 (1992, pl. 34, fig. 7 – as corrected from p. 22) as '*Hi. lusitanicum*', appears to confirm a correlation with the Tethysi Horizon and Barrington, and a correlation with at least the lower part of Bed 19 in the A303 sections is possible based on lithostratigraphical correlations with the new sections and the record of "*Hildoceras cf. sublevisoni*" by Page in Boomer et al. (2009, p. 81).

Bifrons Chronozone (Bed SM21).

Bifrons Subchronozone, Lusitanicum Horizon (Index: *Hildoceras (H.) lusitanicum* Meister).

H. lusitanicum marks the next stage in the evolution of *Hildoceras*, as classically described by Gabilly (1976, including pl. 25, figs 3-6). The incoming of this species in Bed SM20c marks the base of the Lusitanicum Horizon and hence the Bifrons Subchronozone – the top of the Horizon being delineated by the first occurrence of *H. apertum* Gabilly on the top surface of SM21. Occasional *H. falciferoides sensu* Gabilly is also present, with common *Dactylioceras (D.) grp athleticum* (confirming the To14 (*athleticum*) Biohorizon and a rare phylloceratid and a lytoceratid.

Precise correlations with the Barrington and A303 sections are also currently uncertain, although at the former Howarth's figure of a typical *H. lusitanicum* from Bed 26 (1992, pl. 35, fig. 4) suggests that at least part of this unit is of Lusitanicum Horizon age. At the latter site, although not confirmed by sampling at the time, lithostratigraphical correlations (through comparisons of bed thickness, bed ordering) with the new sections suggests that the upper part of Bed 19 may be of similar age.

Bifrons Chronozone (Beds SM22-SM23).

Bifrons Subchronozone, Apertum Horizon (Index: *Hildoceras (Hi.) apertum* Gabilly).

H. apertum is the earliest *Hildoceras* with a distinct spiral sulcus on the whorl side, with typical specimens figured by Gabilly (1976, pl. 26, figs 1-6, 9-11). *H. apertum* first appears on the top surface of SM21, marking the base of the Horizon and persists to SM23b. Occasional *Harpoceras (H.) falciferoides sensu* Gabilly is also present with *Dactylioceras cf. athleticum* in the lower part of the horizon (i.e. indicating an upper limit to To14 (*athleticum*) Biohorizon) and *Peronoceras*, including *Pe. cf. fibulatum* (J. de C. Sowerby) in the upper part (probably indicating the To15, *turriculatum*, Biohorizon), although there is some evidence that the two genera may overlap. The lower part of the Apertum Horizon has also yielded rare *Frechiella subcarinate* (Young and Bird), *Pseudolioceras lythense* (Young & Bird) and a phylloceratid.

As for the preceding Horizon, precise comparisons with the Barrington and A303 sections are not clear, although a possible *H. apertum* figured by Howarth (1992, pl. 37, fig. 6a, b), as "*H. bifrons*", from Bed 26 – presumably, the upper part – suggests a correlation. The presence of "*H. cf. bifrons*" in Bed 22 on the A303, may also suggest a correlation (Page in Boomer et al. 2009).

Bifrons Chronozone (Beds SM24-SM28).

Bifrons Subchronozone, Bifrons Horizon (Index: *Hildoceras* (*H.*) *bifrons* (Bruguière)).

Typical *H. bifrons sensu stricto* is present from Bed SM23c, marking the base of the Horizon, and is succeeded by relatively compressed and weakly ribbed to virtually smooth *H. angustisiphonatum* in the upper part of the Horizon (SM27b-SM28) – with transitional assemblages in SM27a. Specimens of the former are figured by Gabilly (1976, pl. 26, figs 7, 8, pl. 28, figs 1, 2) and by Howarth (1992, including the holotype, pl. 37, figs 1, 2). The holotype was also figured by Gabilly (including pl. 27, figs 6, 7 and pl. 29, figs 1, 2). The species may also have been figured by Howarth as “*Hildoceras bifrons*” (e.g., 1992, pl. 36, fig. 4a, b). Distinctive, involute *Harpoceras* (*H.*) *subplanatum* (Oppel) also appears in this Horizon, replacing *Harpoceras* (*H.*) *falciferoides sensu* Gabilly.

Although rather rare, dactylioceratids including *Peronoceras* sp. occur with *H. bifrons s. s.* in the lower part of the Horizon, with *Porpoceras* sp. in the lower part of the range of *H. angustisiphonatum* Prinz and *Catacoeloceras* sp. in the upper part (= *vortex* Biohorizon (To17) and *crassum-bifrons* (To18) biohorizons respectively). Other records include rare *Phymatoceras* associated with both *H. bifrons* and *Hi. angustisiphonatum* assemblages and possible *Mercaticeras* or *Pseudomercaticeras* associated with the latter. A rare phylloceratid is also present.

The record of *Ha. subplanatum* in the lower part of Bed 27 at Barrington section recorded by Howarth (1992) suggests a general correlation with the Bifrons Horizon, as do the records of “*H. semipolimum*” in association with “*H. aff. bifrons*” and *H. subplanatum* in Bed SM23 and the basal 7 cm of SM24. The horizon is currently not clearly correlated with the A303 bypass sections.

Bifrons Chronozone (Beds SM29 and lower part SM30).

Bifrons Subchronozone, Semipolimum Horizon (Index: *Hildoceras* (*H.*) *semipolimum* Buckman).

True *H. semipolimum* first appears in Bed SM29, marking the base of the Semipolimum Horizon, but persists into the lower part of the succeeding Variabilis Chronozone of the lowest upper Toarcian. The top of the Semipolimum Horizon is indicated by the first occurrence of *Haugia* (see below) marking the base of the latter zone. Typical specimens are figured by Gabilly (1976, pl. 29, figs 3, 4) and Howarth (1992, pl. 38, figs 1a, b, 2a, b, 4a, b, 5a, b). Rare *Catacoeloceras* cf. *crassum* (Young and Bird) and *Phymatoceras*, are also recorded, the former confirming a correlation with the Subboreal To19 (*crassum-semipolimum*) Biohorizon of Page (2004).

The Semipolimum Horizon is recognisable in the A303 bypass sections recorded by Page in Boomer et al. (2009) in the lower part of Bed 24' (Section 2), below the lowest record of *Haugia* grp *variabilis* (d'Orbigny) at 30 cm below the top of the Bed 24' (and around 50 cm above its base). In Section 1, however, in the absence of any record of early *Haugia* the top of the Horizon – and hence the lower-upper Toarcian boundary, cannot be placed – but is likely to lie between 12 and 22 cm above the base of Bed 24. At Barrington, a precise correlation of the Horizon is also unclear as the succession of faunas from the upper part of Bed 27, which would include the Horizon, was not differentiated during sampling. As a result, it is not clear if the specimen of *H. semipolimum* figured by Howarth (1992, pl. 38, figs 4a, b) is of terminal lower or basal upper Toarcian age.

Upper Toarcian Ammonite Stratigraphy

Variabilis Chronozone (Upper 10 cm Bed SM30 and SM31).

Includes Variabilis and Illustris subchronozones (Indices: *Haugia variabilis* (d'Orbigny), *Haugia illustris* (Denckmann)).

The presence of fragments of *Haugia* cf. grp *variabilis* (d'Orbigny) associated with *H. semipolimum*, and rare *Osperleioceras bicarinatum*, *Catacoeloceras* sp. juv. and *Phymatoceras* sp. in the upper 10 cm of Bed SM30, suggests a correlation with the Navis Horizon at the base of the Variabilis Chronozone,

placing the lower-upper Toarcian boundary within Bed SM30. A single, small, round-whorled and unkeeled nucleus from the top 1 cm of SM30 recalls the bouleiceratid *Paroniceras*, but this determination requires confirmation.

Later species of *Haugia*, including *H. grp phillipsi* (Simpson) indicating the Phillipsi Horizon of the succeeding Illustris Subchronozone, are common on the top surface of Bed SM30 and within Bed SM31 above, but frequently display corroded or coated surfaces and an epifauna including serpulid, hence suggesting a period of stratigraphical condensation and long sea-floor residence. The characteristic iron-staining at this level is also a likely indicator of such processes. As there is no clear evidence for *H. jugosa* (J. Sowerby), *H. illustris* (Denckmann) and *H. vitiosa* (Buckman), it appears that not only is the SM30-SM31 level highly condensed, but it may also include non-sequences omitting the Jugosa (upper Variabilis Subchronozone), Illustris (lower Illustris Subchronozone) and Vitiosa (Vitiosa Subchronozone) horizons of Elmi et al. (1997). Whether these horizons are present elsewhere across the region is unclear, however, and records from elsewhere (e.g., in Huxtable 2018) require further confirmation.

Associated ammonoids in Bed SM31, include occasional *Osperlioceras bicarinatum* (Zieten) (especially near the base) and *Phymatoceras*. Rare and ferruginous coated *Catacoeloceras cf. dumortieri* (de Brun) and *Hi. semipolatum* from the base of the bed are certainly derived.

H. grp variabilis from the A303 bypass sections of Boomer et al. (2009), associated with abundant *Hi. semipolatum*, from around 30cm below the top of Bed 24' in the Ilminster bypass Section 2, also indicates the Navis Horizon, with abundant *Haugia grp phillipsi* around 10 cm higher apparently also indicating the Phillipsi Horizon as in the new sections. Howarth's (1992, p.22) level "crowded with large ammonites" within the upper part of Bed 27 at Barrington may also indicate the same level.

Thouarsense Chronozone (Beds SM32-SM34).

Includes Bingmanni, Thouarsense and Fascigerum subchronozones (Indices: *Pseudogrammoceras bingmanni* (Denckmann), *Grammoceras thouarsense* (d'Orbigny) Buckman and *Esericeras fascigerum* Buckman).

As beds SM32 to SM34 appear to be laterally variable, not just lithologically but potentially chronologically as well, the chronozoneal assignment of numbered levels may well vary significantly from section to section, even within the new site. Nevertheless, a general succession of assemblages can still be established with occasional *Pseudogrammoceras cf. bingmanni* in the lower part of Bed SM32 indicating the Bingmanni Subchronozone and Horizon at the base of the Thouarsense Chronozone is represented (Bed SM32, at least in part). In the lower part of the overlying SM33, abundant and often fragmentary *G. grp thouarsense* indicates the succeeding Thouarsense Subchronozone, which probably includes the upper Thouarsense Horizon (there is currently no clear evidence of the intervening Doerntense Horizon (Index: *Pseudogrammoceras doerntense* (Denckmann))). The succeeding Fascigerum Subchronozone and Horizon is proven by fragmentary *Esericeras cf. fascigerum* from the top 2-3 cm of Bed SM33 and more complete specimens from Bed SM34. *Hammatoceras* sp. is also present in the latter bed. No younger, stratigraphically diagnostic ammonoid faunas have been recovered in situ from the Seavington sections described here, including the Fallaciosum Subchronozone at the top of the Thouarsense Chronozone (Index: *P. fallaciosum* (Bayle)), although a single *Phylseogrammoceras dispansum* (Lycett) (Dispansum Chronozone) is reported by Huxtable (2012) from what may be equivalent to Bed SM34.

The presence of abundant *Grammoceras grp thouarsense* and *G. striatulum* (J. de C. Sowerby) from 5-30 cm below the top of Bed SM24 and possible *Esericeras* in the upper 5cm part of Bed 24 on the Ilminster bypass (Section 1; Page in Boomer et al. 2009) indicates correlation with the Thouarsense and Fascigerum subchronozones respectively, although clear evidence of the Bingmanni Subchronozone seems to be lacking. "*Grammoceras* spp." in, presumably the uppermost part of Bed 27 at Barrington – as recorded by Howarth (1991, p. 22) - indicates the Thouarsense Subchronozone,

at least, is present, although the records of *Pseudogrammoceras* spp. and *Grammoceras* spp. in Bed 28 above do not confirm the Fallaciosum Subchronozone. The presence of *Hammatoceras* sp., however, suggests a level no older than Fascigerum Subchronozone. *Phylseogrammoceras dispansum* in the basal Bridport Sands Formation, around 73 cm higher, would confirm the succeeding Dispansum Chronozone.

Calcareous microfossil biostratigraphy and assemblage composition

Bed-by-bed sampling was undertaken for most of the clastic units in the Seavington section. Some were collected as bulk samples representing a single bed, others as blocks that were subsequently split into much higher-resolution samples, especially around Bed SM4.

All samples were disaggregated easily using standard preparation techniques, usually just water or freeze-thaw with water. Preservation of foraminifera and ostracod specimens was generally good with fine-scale ornamentation preserved. However, SEM analysis reveals that calcite from the foraminifera and ostracods may have undergone some recrystallisation. Beds SM1-4 yielded mainly cream-coloured, often opaque, calcitic microfossils indicating a higher iron content than the younger beds that exhibited white to light grey, translucent calcite preservation. Processed residues often contain significant quantities of micro-nodular carbonate and overgrown calcitic bioclasts (mainly bivalves, gastropods, ophiuroids and echinoderms, as well as overgrown microfossils), making it difficult to accurately assess quantitative changes in microfossil specimen abundance. The stratigraphic ranges of the most abundant and stratigraphically significant species of foraminifera and ostracods are shown in figure 6, key taxa are discussed below and many are also illustrated in figure 7. The continued presence of benthic microfossils throughout the CIE, albeit with a much-reduced abundance and diversity during that interval indicates at least some limited dissolved oxygen availability during this period. Figure 8 illustrates the major changes in benthic microfaunal composition through the Seavington section.

Microfossil stratigraphy and assemblage composition

Early Jurassic ostracods and foraminifera have been recorded previously from south Somerset (Boomer 1992, Boomer *et al.* 2009) based on the temporary exposures of the nearby Ilminster bypass, though only ostracods were figured in those publications. The microfossil assemblages at Seavington are generally abundant (100-200 foraminifera counted in most samples) and diverse (see figure 8A and 8B). Independent chronostratigraphy is provided by the ammonites (figure 3) against which the observed microfossil ranges can be compared. Foraminiferal biozones JF12-16 (Copestake & Johnson 2014) and ostracod biozones OJ8-OJ9 (Ainsworth *et al.* 1998) are recognised within the Seavington section, although the transition between JF-12 to JF13 is uncertain, occurring within the mid-upper part of Bed SM4, an interval of just 20-25 cm, the uncertainty probably reflects the condensed lithology at this level. Although not all foraminiferal marker species are present, the data and the foraminiferal biozones based upon them, are consistent with the ammonite chronostratigraphy.

Both species richness and faunal turnover (last appearances plus first appearances) are high in the Spinatum Chronozone, the latter is in part an artefact of the 'appearance' of taxa at the base of the section but 20% of the turnover in the lowest 4 samples can be ascribed to extinctions that form part of a late Tenuicostatium Chronozone turnover, which is discussed in Copestake & Johnson (2014). Species richness in the ostracods and foraminifera decreases through to the onset of the CIE, which marks the low point in both groups. Although the foraminifera are continually recorded throughout the CIE interval (2-5 species), ostracods are absent from the earliest sample within the CIE, gradually recovering to three species by the end. Although our records do not confirm the occurrence of complete anoxia at any level, some degree of dysaerobia is likely through the CIE. It also suggests that the most severe conditions were experienced in the earliest stages, around Bed SM4b, with the fauna gradually recovering after this. Peaks in faunal turnover are also noted immediately after the CIE, with roughly equal numbers of first and last appearances.

The foraminiferal assemblages are typically dominated by nodosariid taxa, very few agglutinating specimens were recorded and there were no records of aragonitic-walled robertininid taxa (i.e., *Reinholdella*). It is unclear whether this is a diagenetic or an environmental signal, as the group is common in the earliest Toarcian of the Wessex Basin (offshore well 97/12-1, Ainsworth & Riley 2010). Although other aragonitic material (e.g., ammonite phragmocones) have not survived at this site, calcitic taxa such as *Lenticulina muensteri* certainly occur all the way through, many of which are very well-preserved. Some encrusting *Nubeculinella*-type foraminifera are observed on ammonite shells.

The Seavington section is notable for the occurrence of species that are recorded from the UK for the first time or have a limited geographical distribution in this country. Somerset is the only previously recorded location in the UK for *Planularia obonensis* (= *P. cornucopiae* Moore 1866; Boomer et al. 2009; noted by Copestake & Johnston 2014), a species more commonly observed in Spain (Ramirez & Herrero 2015; Ruget 1982). It is recorded at Seavington from a short interval (beds SM4a-SM6) from just prior the CIE to just after its termination (figure 6) and is one of the few taxa to be recorded almost consistently through that event.

Similarly, *Lenticulina payardi* has only previously been recorded from a single UK locality at Robin's Wood Hill, Gloucestershire (Copestake & Johnson 2014) where, in the absence of ammonites, it was assumed to be of early Serpentinum Chronozone age. The present study confirms, based on associated ammonites, an age of early Exaratum Subchronozone and a short stratigraphical range here, between beds SM6 and SM8. *L. payardi* is commonly recorded from sections in central-eastern Spain (Ruget 1982; Herrero 1993a, b) and southern Germany (Riegraf 1985), where it ranges throughout the Serpentinum Chronozone, however, at Seavington, it displays a shorter range, within this ammonite chronozone. In central-eastern Spain, this species is restricted to the Serpentinum Chronozone (Herrero 1993a, b), ranging into the JF14 biozone. The foraminiferal assemblages above the CIE level become dominated by *Planularia protracta*, *Astacolus chicheryi*, *P. obonensis*, *Citharina longuemari* and *Lenticulina quenstedti*, together with the continued abundance of *L. muensteri*.

Paralingulina sp. A is a rare species, but it has been previously recorded from Gloucestershire and Lincolnshire in the UK (Copestake, unpublished data) and from DSDP Site 547 offshore NW Morocco (Riegraf et al. 1984, as "*Lingulina* cf. *testudinaria*") reinforcing the palaeogeographical connections at this time. It appears to be a useful marker, having a short stratigraphical range of latest Spinatum Chronozone to Tenuicostatum Chronozone. This new species will be described in full in a later publication.

The ostracods are characteristic of uppermost OJ8 and the lower part of OJ9 Jurassic Ostracod biozones of Ainsworth et al. (1998), the ostracod abundance and diversity are too low to make any more certain stratigraphic interpretations. The most significant event in the ostracod record is the disappearance (extinction) of the metacopid ostracods (e.g., *Ogmoconcha convexa*, *Ogmoconchella* spp.) at the top of Bed SM4a. This is coincident with the onset of the CIE, and contemporaneous with the same, global event recorded elsewhere (e.g., Mochras Borehole, Boomer 1991). The CIE also coincides with marked faunal turnover within the ostracods. Only one, relatively rare, ostracod species, *Trachycythere verrucosa*, (not shown on the range-chart, figure 6) is recorded both prior to and after, but not within, the CIE at Seavington.

At the top of the CIE (Bed 4d) an ostracod assemblage is recorded that is dominated by *Liasina lanceolata*, yet the species does not occur in any other samples from Seavington. The species also dominates a single monospecific assemblage contemporaneous with the onset of the CIE in the Mochras Borehole (Boomer 1991) but is also a relatively minor component of other assemblages at that locality. These two records may relate to a tolerance of reduced dissolved oxygen conditions or a related environmental condition. Ainsworth & Riley (2010) recorded *L. lanceolata* together with species of *Reinholdella* in the earliest Toarcian and noted that it was the only species recorded in the

'Paper Shales' (presumably part of the CIE) of the Beacon Limestone Formation in the Wessex Basin, offshore well 97/12-1.

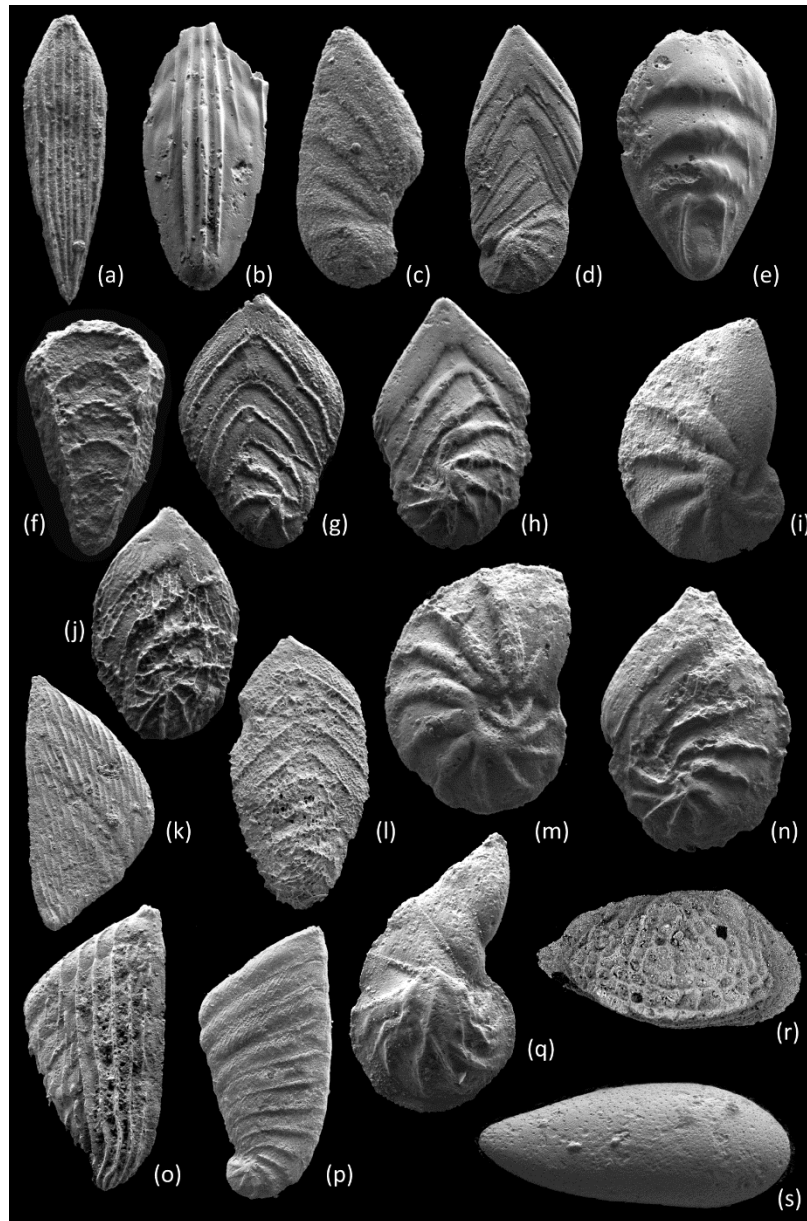


Figure 7. Key calcareous microfossil taxa recorded in the Seavington St Michael section.

(a) *Ichthyolaria terquemi squamosa*, sample HUR003 (Bed SM2), 300 µm long. BU5474. (b) *Ichthyolaria terquemi mediumcostata*, HUR003 (Bed SM2), 300 µm long. BU5475. (c) *Planularia protracta*, HUR008 (Bed SM8), 300 µm long. BU5476. (d) *Planularia protracta* (flabelline form), HUR016 (Bed SM15), 300 µm long. BU5477. (e) *Paralingulina* sp.A., HUR004 (Bed SM4a), 300 µm long. BU5478. (f) *Paralingulina occidentalis*, HUR002 (Bed SM2), 300 µm long. BU5479. (g) *Palmula deslongchampsii*, HUR016 (Bed SM15), 300 µm long. BU5480. (h) *Planularia chicheryi*, HUR019 (Bed SM20), 300 µm long. BU5481. (i) *Astaculus chicheryi*, HUR015 (Bed SM14), 300 µm long. BU5482. (j) *Lenticulina dorbignyi*, HUR019 (Bed SM20), 300 µm long. BU5483. (k) *Citharina colliezi*, HUR021 (Bed SM29), 300 µm long. BU54845. (l) *Planularia pauperata*, HUR010 (Bed SM10), 300 µm long. BU5485. (m) *Astaculus* sp.A., HUR017 (Bed SM16), 300 µm long. BU5486. (n) *Astaculus* sp. B., HUR019 (Bed SM20), 300 µm long. BU5487. (o) *Citharina longuemari*, HUR021 (Bed SM29), 300 µm long. BU5488. (p) *Planularia obonensis*, HUR011 (Bed SM6), 300 µm long. BU5489. (q) *Lenticulina payardi*, HUR011 (Bed SM6), 300 µm long. BU5490. (r) *Kinkelinella tenuicostata*, HUR004 (Bed SM4a), 300 µm long. BU5491. (s) *Liasina lanceolata*, HUR004 (Bed SM4a), 300 µm long. BU5492.

Foraminiferal biozonation

Foraminiferal biozones JF12-JF16 (Copestake & Johnson 2014) are recognised within the Seavington section. Although not all known latest Pliensbachian to Toarcian foraminiferal marker species that define these biozones are present, the data and the foraminiferal biozones based upon them, are consistent with the ammonite chronostratigraphy. “Base occurrence” refers to an up-section incoming or evolutionary inception, while “top occurrence” represents the up-section disappearance, which may relate to extinction.

JF12 Biozone (Subbiozones JF12a and JF12b)

Definition of base: The base of *Saracenaria sublaevis sublaevis* marks the base of the biozone in the original zonal definition: the lowest occurrence of this taxon is recorded in Bed SM2 (sample HUR002, see supplementary data for details of sample codes and bed numbers), however, the base of the biozone probably occurs below the base of the studied section based on the ammonite chronozone interpretation. The base occurrence of *Planularia obonensis* in Bed SM4a (sample HB01-2) is diagnostic of an intra JF12 biozone position (base of the JF12b subbiozone), close to the base of the Tenuicostatum Chronozone, as in this section.

Definition of top: Base of overlying biozone.

Remarks: The occurrence of *P. obonensis* in the studied section is important as this species has only been previously recorded in Britain in the vicinity of this site (see above).

The top of the JF12 biozone was previously placed at the top of the Tenuicostatum Chronozone (Copestake & Johnson 2014), however, at Seavington, species characteristic of this foraminiferal biozone extend into the lower part of the Serpentinum Chronozone, Exaratum Subchronozone. This is most likely due to the dysoxic conditions represented by beds SM4b to SM4d at Seavington compared to the anoxic conditions seen elsewhere.

JF13 Biozone

Definition of base: Top occurrence of *Ichthyolaria terquemi squamosa* (Bed SM4c, sample HB01-7), supported by the base occurrence of *Lenticulina payardi* above this, in Bed SM6 (sample HUR007).

Definition of top: base of overlying biozone.

Remarks: The occurrence of *L. payardi* in this section is the first record of the species from the UK, that is tied to ammonite occurrences (see discussion above). The presence of common to abundant *Paralingulina tenera tenera*, up to the lower part of the JF13 biozone in this section, is unusual. This taxon is not usually seen in high numbers higher than the top of the JF12 biozone, at the top of the Tenuicostatum Chronozone (Copestake & Johnson 2014).

JF14 Biozone

Definition of base: Top occurrences of *P. obonensis* and *L. payardi*.

Definition of top: base of overlying biozone.

Remarks: The top occurrences of *P. obonensis* and *L. payardi* define the base of the JF14 biozone, following Copestake & Johnson (2014). *L. payardi* is known to range to the top of the Serpentinum Chronozone (Copestake & Johnson 2014), however, at Seavington the upper limit of its range is older, within the Serpentinum Chronozone. *P. obonensis* occurs between the Tenuicostatum Chronozone and the lower Serpentinum Chronozone in Teruel, eastern Spain (Herrero 2011) but is confined to the former chronozone in other Spanish sections (Herrero 1993a). Boutakiout (1990) and Bejjaji *et al.* (2010) reported the species from the “Serpentinus Zone” of Morocco (Middle Atlas).

JF15 Biozone

Definition of base: Base occurrence of *Lenticulina dorbignyi*.

Definition of top: base of overlying biozone.

Remarks: The base occurrence of *L. dorbignyi* marks the base of the JF15 Biozone, at the base of the Bifrons Chronozone here and regionally within the UK (Copestake & Johnson 2014).

JF16 Biozone

Definition of base: Base occurrence of *Palmula tenuistriata*.

Definition of top: not seen.

Remarks: The base occurrence of *P. tenuistriata* has been used to define the base of the JF16 biozone (Copestake & Johnson 2014). The species is a good marker for the middle Toarcian–Aalenian throughout north-west Europe, although it is most common in the upper Toarcian (Copestake & Johnson 2014). In Spain, it occurs from the Bifrons Chronozone (middle Toarcian) to the upper Toarcian (Rugé 1982; Herrero 1993a). The Mochras record from the upper Toarcian is the only previous British record of this species. The occurrence of the species in the Bifrons Chronozone at Seavington is comparable to its base occurrence at the same level in Spain, reflecting the affinity of the Seavington section with those in Spain.

Foraminiferal morphogroups and palaeoenvironments

Benthic foraminiferal morphogroups have been used to infer past changes in bottom water oxygenation (Jones & Charnock 1985; Nagy 1992; Rosoff & Corliss 1992) with a number of studies focussing on Early Jurassic benthic foraminiferal assemblages (Bartolini *et al.* 1990; Mailliot *et al.* 2009; Reolid *et al.* 2012a, b; 2013; 2019; Rita *et al.* 2016; Jozsa *et al.* 2018). Such interpretations are largely based on modern collections in tandem with dissolved oxygen records or where that has been interpreted through sedimentology. While the precise controls on species distributions cannot be unequivocally proven beyond those modern assemblages, it is clear that changes in the abundances of different morphogroups from fossil assemblages are often associated with known changes in bottom water conditions, including the early Toarcian OAE (e.g., Reolid *et al.* 2012a, b; 2019; Reolid 2020).

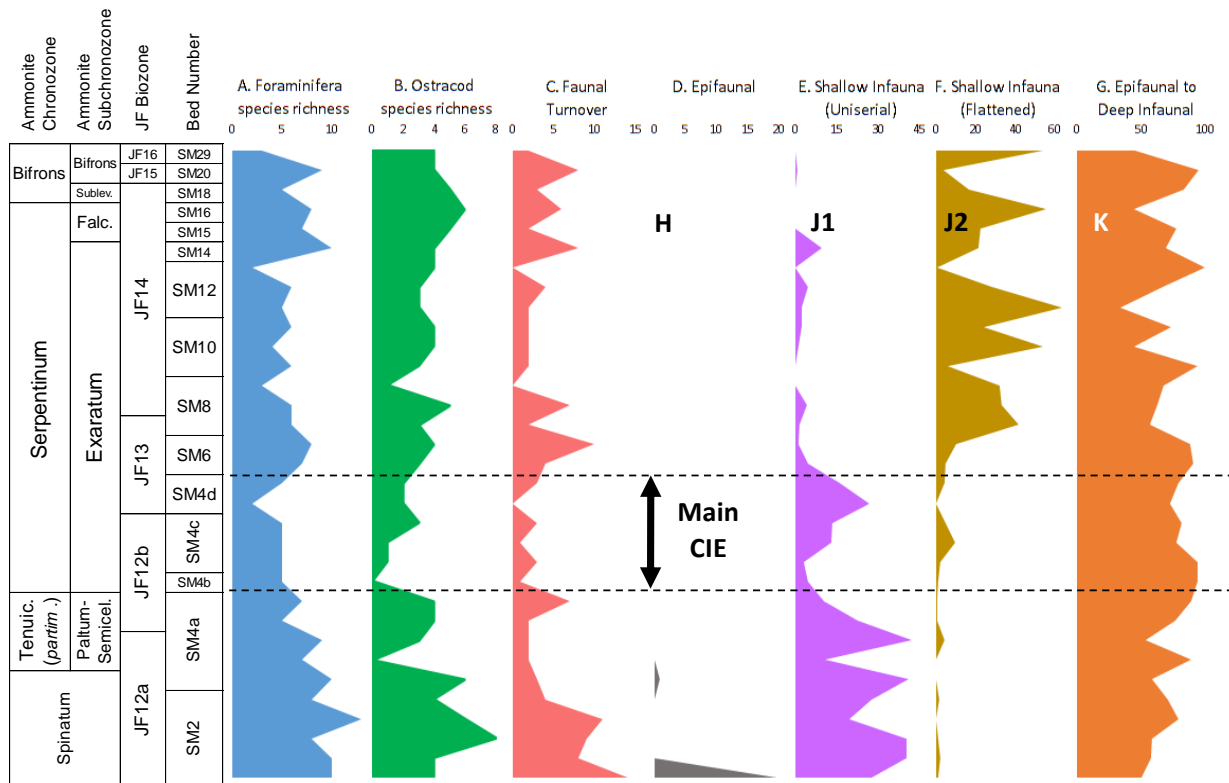


Figure 8. Changing faunal composition of the calcareous microfossil assemblages. Plots A and B illustrate changing diversity as species richness (8A Foraminifera, 8B Ostracoda). Plot C is a composite record of faunal turnover, calculated by adding the number of species first and last appearances datums in each sample. Plots D-G are percent abundances of benthic foraminiferal morphogroups (see Reolid *et al.* 2019 for details), D. ‘Morphogroup H’ (epifaunal taxa), E. ‘Morphogroup J1’ (shallow infaunal, uniserial tests), F. ‘Morphogroup J2’ (shallow infaunal, flattened taxa) and G. ‘Morphogroup K’ (mostly biconvex taxa, ecology ranging from epifaunal to deep infaunal).

Changes in the foraminiferal morphogroup composition at Seavington are illustrated in figure 8D-G with the most pronounced change occurring either side of the CIE. Initially, the presence of the planispiral, epifaunal species *Spirillina tenuissima* (morphogroup H, figure 8D) in the lowermost sample distinguishes that assemblage from all others and perhaps points to a relatively different setting compared to younger sampled horizons.

Subsequent samples are usually dominated by generalist taxa (morphogroup K), typified by the biconvex *Lenticulina* group (figure 8G) which have been interpreted as having a range of ecological modes from epifaunal to deep infaunal (Reolid 2008). Specimens of the *Lenticulina muensteri* plexus dominate most samples, even through the CIE where abundances exceed 70% of each assemblage. This points to higher than expected levels of oxygenation at Seavington during the CIE interval compared to other UK sites. The remaining elements of the assemblages can be assigned to morphogroups J1 and J2 of Reolid *et al.* (2012a), these are interpreted as shallow infaunal taxa but there is clearly a switch between the importance of the two groups before and after the OAE.

Morphogroup J1 (figure 8E) possess elongate uniserial tests and is most abundant before the interval of the CIE, decreases rapidly at the onset but stages a recovery within it, subsequently it constitutes only a very minor component. Conversely, morphogroup J2 (figure 8F) are characterised by elongate flattened tests and these only occur in significant number post-CIE, become a significant proportion of the later assemblages.

The biological link between test morphology and environmental conditions remains unclear for these Early Jurassic assemblages, however, the shift from J1 to J2 Morphogroup assemblages between the Tenuicostatum and Serpentinum chronozones in the present study, suggests that there was a distinct change in benthic ecosystems during this time, possibly relating to changing bottom-water oxygenation or organic carbon flux to the sea-floor. A similar pattern, over the same stratigraphic interval, was observed by Reolid *et al.* (2012a, figure 6) from the Early Jurassic of Algeria, morphogroup J1 dominating the shallow infauna before the CIE and J2 afterwards. The record from the Mochras Borehole (Reolid *et al.* 2019) is not dissimilar in this respect and although the absence of *Reinholdella* at Seavington (Morphogroup G, Reolid *et al.* 2019) is a notable difference, there is still a broadly similar faunal response to the same palaeoceanographic events (ocean warming, stratification and reduced dissolved oxygen levels) across 100s of kilometres.

Palynological biostratigraphy and assemblage composition

A selection of 21 samples from Seavington were examined for palynological content (figure 9). The samples were processed using standard methods involving acid digestion using HCl, HF and HNO₃ (Wood *et al.* 1996). An initial count of 200 specimens was made and then the remainder of the slide scanned for any other taxa that were not encountered in the initial count. A percentage estimation of the main kerogen components (exinite, vitrinite, inertinite, amorphous organic material) was determined to aid interpretation of the depositional environments.

In general, the preservation of the palynomorphs was moderate to good, with most of the samples being reasonably productive, terrestrial taxa being by far the most dominant forms recorded and pollen being far more common than pteridophyte spores. Marine taxa are relatively sparse, apart from sphaeromorph acritarchs, which are present in some numbers throughout the section and recorded at certain horizons in considerable numbers. These acritarchs are common through the Serpentinum Chronozone to Spinatum Chronozone interval, between Bed SM14 and SM2 and are most abundant between beds SM6 and SM4c, within and immediately above the CIE. This is consistent with the known abundance of such forms in association with the CIE elsewhere. Houben *et al.* (2017) recorded the sphaeromorph (as *Halosphaeropsis liassicus*) acme in the “Falciferum Zone” (equivalent to the Serpentinum Chronozone) in onshore UK and in the offshore North Sea region, immediately above and within the CIE. In the biozonation scheme of Partington *et al.* (1993) the last occurrence of common

sphaeromorph acritarchs defines the top of the PJ6 biozone, PJ6c subbiozone, and an intra Serpentinum Chronozone level, with the base common occurrence within the Tenuicostatum Chronozone (base of the PJ6 subzone), as at Seavington.

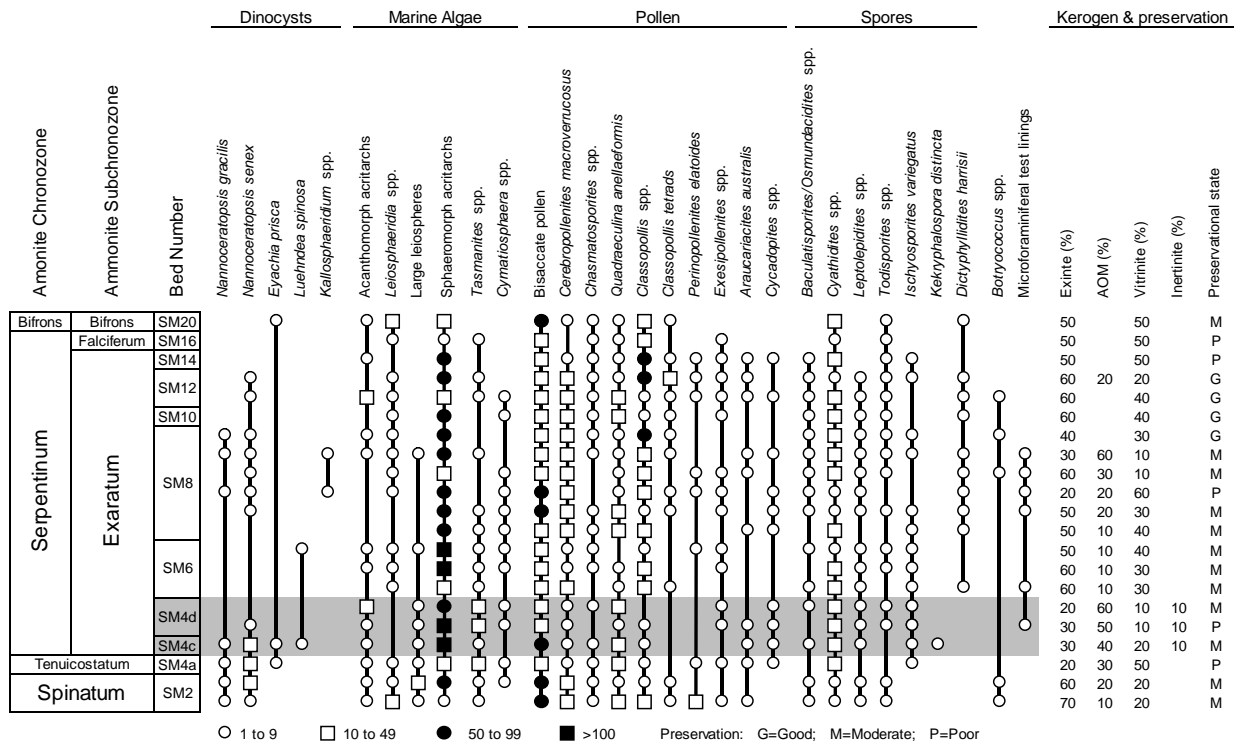


Figure 9. Semi-quantitative palynostratigraphy of the Seavington Section (selected taxa only), grey shaded interval represents the main CIE.

Dinocysts are low in both abundance and diversity, but the stratigraphic occurrence of zonal markers *Luehndea spinosa*, albeit in just two samples, and *Nannoceratopsis senex* confirms the presence of dinoflagellate biozones DSJ6 (in part) to at least DSJ7 (Poulsen & Riding 2003), consistent with other biostratigraphic data from Seavington. In the Partington *et al.* (1993) biozonation scheme the last occurrence (extinction) of *L. spinosa* occurs within their PJ6 zone, PJ6c subzone, within the Serpentinum Chronozone, as it does at Seavington. Riding & Thomas (1992) considered the extinction of *L. spinosa* to be in the Serpentinum Chronozone (Exaratum Subchronozone) in Yorkshire, confirmed by Charnock *et al.* (2001). The species ranges to this level in the Mochras Borehole, north Wales, where it occurs commonly (Van de Schootbrugge *et al.* 2005). Houben *et al.* (2017) showed its extinction to occur in the basal part of the “Falciferum Zone” (equivalent to the Serpentinum Chronozone) in onshore UK. Riding *et al.* (1994) noted the association of *L. spinosa* in the Southern North Sea Basin with the abundance of small sphaeromorph acritarchs, probably referable to *Halosphaeropsis liassicus*.

The first occurrence of *Eyachia prisca* is seen at Seavington in sample SM4a (Tenuicostatum Chronozone), however, this species has been recorded to range no older than the Bifrons Chronozone in onshore UK sections (Riding & Thomas 1992), at which level the datum was drawn by Charnock *et al.* (2001) in the Viking Graben (North Sea).

Palynological depositional environments

All samples examined contained marine markers, either dinocysts or acritarchs, in varying numbers and states of preservation. Palynomorph evidence suggests that there may have been two dysaerobic marine intervals, the first corresponding to the main CIE (beds SM4c-d) and then again in the two upper samples of Bed SM6. The evidence for this interpretation relates to the high numbers of

sphaeromorph acritarchs and abundant amorphite recorded over these two intervals. The two intervals are separated by a single sample (base of SM6) which has a relatively high percentage of *Classopollis* spp., many of which are recorded as tetrads, suggesting very little transport or rapid burial, presumably in a relatively nearshore, marine environment.

The succeeding younger samples in the section suggest relatively well-oxygenated, marine, shelf conditions. It is noted, however, that one sample near the top of Bed SM8 contains a relatively high percentage of vitrinite compared to the other kerogen components in the sample. Such an assemblage may be indicative of a horizon that has undergone high oxidation and/or reworking of material (Fisher 1980) where vitrinite has been preferentially preserved and as such may represent a small non-sequence. The palynological samples from beds SM14 and SM16 are very sparse and poorly preserved, possibly reflecting more calcareous units than the other samples in the section. The youngest sample examined (Bed SM20) displays relatively low percentage of exinite in a poor state of preservation, including sparse dinocysts. This, together with higher quantities of vitrinite and inertinite, may indicate increasing energy in the marine shelf environment towards the top of the section and would fit with the known transition to the more proximal Bridport Sand Formation in this area (see figure 3).

Nannoplankton biostratigraphy and assemblage composition

Fourteen samples have been examined from an interval that encompasses the lower part of the Seavington section, with the aim of recording nannoplankton response to early Toarcian events. The nannoplankton were analysed using smear slides and standard light microscope techniques (Bown & Young 1998). Stratigraphic distribution data was collected semi-quantitatively, with species abundances estimated per field of view (FOV) after looking at least five slide transects (thousands of fields of view). Species range-charts are presented in figure 10. Taxonomy follows *Nannotax* (<http://www.mikrotax.org/Nannotax3>). Nannofossil biostratigraphy is described with reference to the Jurassic NJ biozones of Bown & Cooper (1998).

Nannoplankton diversity is high (averaging 29 species per sample) and community composition is relatively normal for this interval, with common *Crepidolithus* (*C. crassus*), *Biscutum* (*B. novum*) and *Lotharingius* (*L. hauffii*). Particularly diagnostic assemblage components include frequent large *Biscutum* species (*B. finchii*, *B. grande*), frequent and diverse *Calyculus* and common *Sollasites*, especially *S. arctus*. Species richness is at its highest immediately before and immediately after the CIE and preservation is moderate to good throughout (see figure 11 with images illustrating the high quality of preservation).

The stratigraphic ranges and semi-quantitative abundance data presented in figure 10 confirm the presence of Jurassic nannofossil subbiozone NJ5b (*Crepidolithus impontus* present at the base of the section) and NJ6 Biozone, based on the rare occurrence of *Carinolithus superbus* in Bed SM8. This is consistent with previous Boreal studies, e.g., Bown & Cooper (1998). The data includes relatively subtle shifts in assemblage composition, with increasing abundance and diversity of *Calyculus* notable, but no major floral or environmental crisis in response to the T-OAE is apparent. Three murolith species (*Crucirhabdus primulus*, *Mitrolithus* cf. *M. elegans* and *Parhabdololithus liasicus*) disappear in the sample below the OAE (with the 2 or 3 occurrences in Bed SM4c likely reworked), which is consistent with previous biostratigraphic work (Bown & Cooper 1998), although these taxa have been reported stratigraphically higher in some Tethyan sections (Ferreira et al. 2019).

Immediately above the OAE interval, the section records the highest occurrences of *Crepidolithus granulatus* (Bed SM6), followed by four biscutatean species (*B. finchii*, *B. grande*, *Similiscutum avitum* and *S. orbiculus*; Bed SM8). This clustering of last occurrences near the top of Bed SM8 may indicate a hiatus, which is also suggested by increased vitrinite phytoclasts in the palynology residues. Evidence for decreasing nannoplankton abundance immediately after the CIE may reflect sediment dilution due to increasing runoff following the hyperthermal, although it is only observed in a single sample. Neither the community composition nor the relative abundance of key taxa provides strong evidence

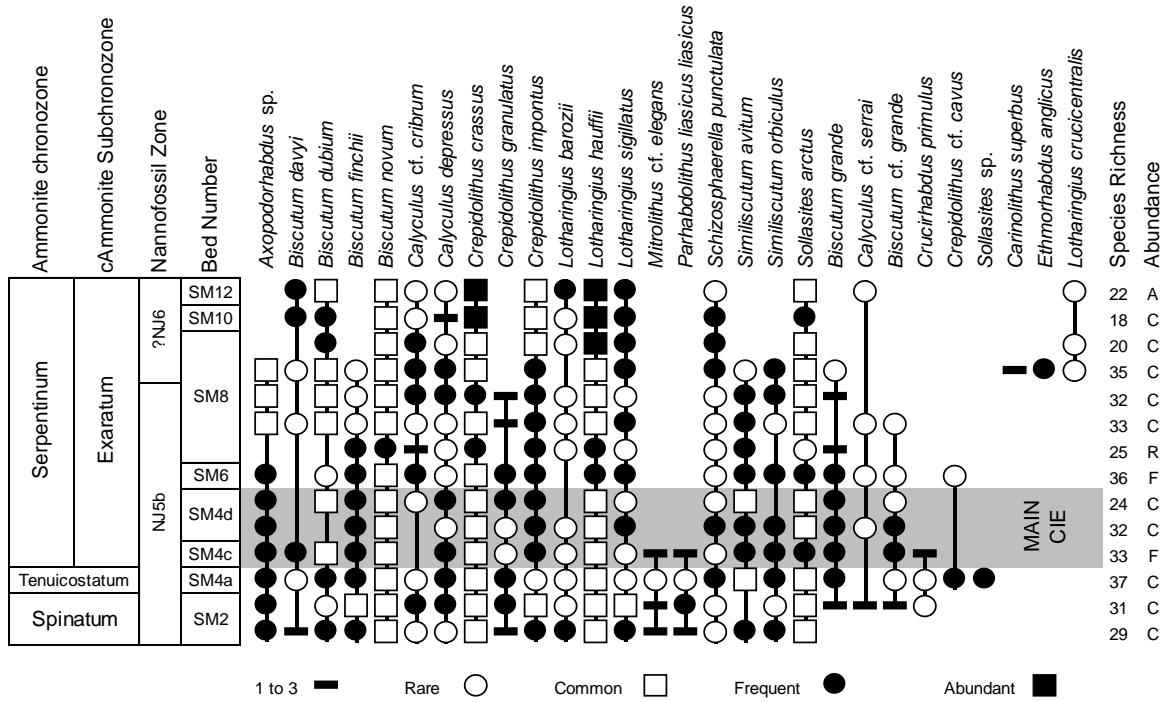


Figure 10. Calcareous nannofossil distribution (selected taxa only) across the T-OAE at Seavington, Somerset. Greyed interval indicates the main Carbon Isotope Excursion. Abundance: A=Abundant (>10 specimens per FOV), C=Common (1-9 specimens per FOV), F=Frequent (1 specimen per 2-10 FOVs), R=Rare (1 specimen per >11 FOVs). Uncertainty in recognition of Zone NJ6 due to low abundance of marker *C. superbus*. (Full range-chart available in Supplementary material).

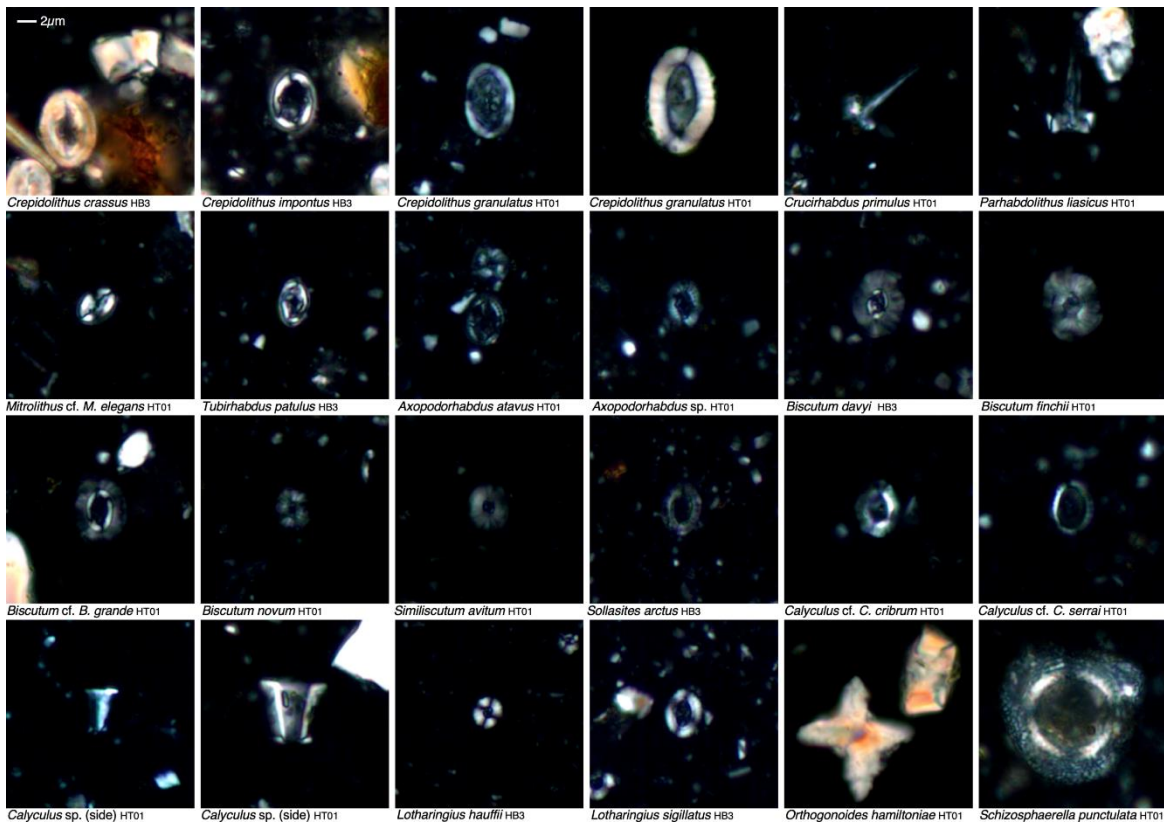


Figure 11. Key nannoplankton taxa recorded from the early Toarcian exposure at Seavington St Michael, Somerset.

for stratification across the period before, during or after the CIE, although relative abundance changes in some minor taxa provide evidence for limited impacts. Overall, the assemblages point to relatively well-mixed, open water setting throughout the earliest Toarcian of the area.

Stable-isotope Geochemistry

The negative Carbon Isotope Excursion (CIE) is one of the most distinctive features of the T-OAE and is recorded in both organic carbon and inorganic fractions from marine and terrestrial environments, reflecting both the atmospheric and marine reservoirs (Hesselbo & Pienkowski 2011). Due to this global response, the CIE can be recognised in successions that do not exhibit clear sedimentary evidence for extreme dysoxia (i.e., black shales). The T-OAE is correlated with biotic perturbations (particularly extinctions and changes in assemblage composition), demonstrating the widespread impact of the OAE on marine communities (Little & Benton 1995; Gómez & Goy 2011; Caswell *et al.* 2009). At sites such as Seavington, it is clear from the benthic faunal record that although bottom water environmental conditions deteriorated, they never became anoxic and although the T-OAE interval itself may not be clearly recognised from the sedimentology, it is evidenced by the CIE. At Seavington, a profile of $\delta^{13}\text{C}$ from the inorganic fraction ($\delta^{13}\text{C}_{\text{calcite}}$) was prepared using bulk sediment samples from the clastic units only, as the limestone $\delta^{13}\text{C}_{\text{calcite}}$ may be affected by diagenetic cements.

The stable-isotope compositions were determined using a continuous-flow Isoprime/Elementar IRMS with Multiflow preparation line at the University of Birmingham GEMS facility. Sample size varied to obtain sufficient carbonate material for analysis but was usually in the range 0.5 to 2.0 mg. Results are standardised to Vienna PDB using IAEA NBS-18 and NBS-19. Internal reproducibility was better than 0.08‰ $\delta^{13}\text{C}$ and 0.15‰ $\delta^{18}\text{O}$. A subset of those samples was then investigated for the $\delta^{13}\text{C}$ of the organic component ($\delta^{13}\text{C}_{\text{org}}$) through the CIE interval identified from the $\delta^{13}\text{C}_{\text{calcite}}$ record. Samples were decarbonated in 10 ml 5% HCl for at least 24 hrs. The acid was decanted and the samples repeatedly rinsed, each followed by at least 6 hrs settling. The dried residue was analysed on an Elementar Pyrocube, with combustion at 850°C, internal precision was usually better than 0.05‰ $\delta^{13}\text{C}$. The resulting carbon stable-isotope curves for the Seavington section are illustrated against the main log in Figure 12.

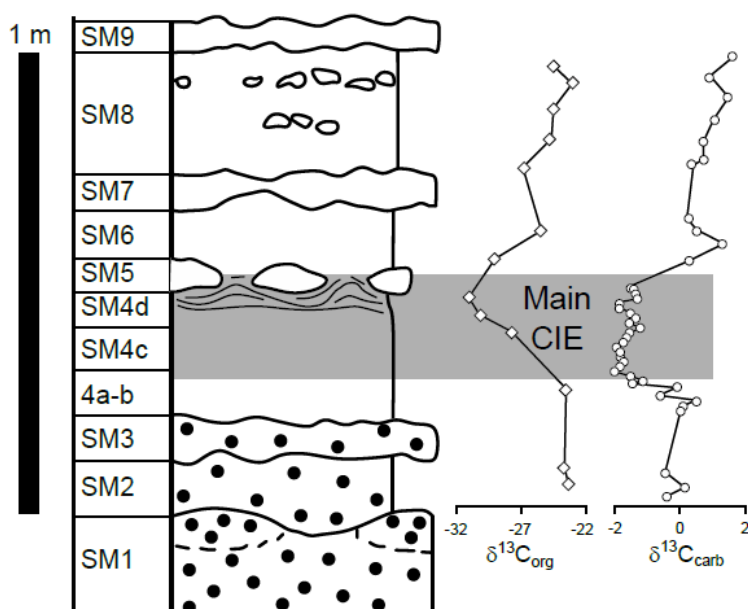


Figure 12. Carbon stable-isotope records of organic and inorganic fraction through the early Toarcian section at Seavington, Somerset.

The isotope records demonstrate a single, clear CIE through beds SM4c to SM6. Although a lowermost Toarcian hiatus is suggested at the top of Bed SM3 based on the ammonite biostratigraphic evidence,

the stable-isotope record suggests that 'pre-excursion' values are recorded after that hiatus indicating that the full CIE interval may be captured in this data, albeit condensed at this locality. The hiatus is further evidenced by the absence of the latest Pliensbachian to earliest Toarcian CIEs noted by Littler *et al.* (2020). The observed CIE covers an interval of approximately 80 cm here at Seavington compared to c.45 m in the Mochras Borehole (west Wales) and c.10 m in the Cleveland Basin (Yorkshire). The $\delta^{13}\text{C}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{org}}$ records also show some degree of decoupling, with a more rapid onset and time to peak CIE values in $\delta^{13}\text{C}_{\text{calcite}}$ whilst the $\delta^{13}\text{C}_{\text{org}}$ is somewhat delayed. This pattern is somewhat similar to paired $\delta^{13}\text{C}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{org}}$ isotope records from the PETM Cenozoic hyperthermal, which have been attributed to the rapid response of local pelagic carbonate production, versus the transport and mixing of terrestrial and marine organic carbon, including the input of pre-event terrestrial carbon, imparting a delayed time to peak $\delta^{13}\text{C}_{\text{org}}$ CIE values (e.g., Dunkley Jones *et al.* 2018).

Discussion

The sediments at Seavington and the local area represent relatively unique facies for the Toarcian of the UK. The total thickness indicates relatively low sedimentation rates for this period (about 9 Ma), the same stratigraphic interval being represented by about 4-5 m on the Dorset Coast (Simms 2004) and about 70-80 m in Lyme Bay (Ainsworth & Riley 2010). These differences likely reflect both palaeotopography and syn-sedimentary structural controls. Low sedimentation rates at Seavington also reflect low detrital input, probably associated with a depositional setting some distance from detrital supply and therefore it is interpreted as a relatively deep-water (mid- to outer shelf) environment. A distal setting with hemipelagic conditions, is also suggested by the high abundance of well-preserved ammonites and the abundant, well-preserved calcareous nannoplankton assemblages. Similarly, the relatively high abundance of the foraminifera genus *Lenticulina* echoes the observations of Canales *et al.* (2014) who demonstrated that high abundances of that genus were typical of the more proximal parts of the Lusitanian Basin through the Early to Middle Jurassic interval.

The macrobenthos are also consistent with mid- to outer shelf conditions including occasional echinoderms (some crinoid ossicles, echinoid spines and ophiuroid elements in residues), micromorphic brachiopods and inoceramid bivalves. Trace fossils are not common but *Chondrites* and *Diplocraterion* have been observed. Despite the evidence for a relatively open water depositional setting, the palynological evidence points to a more restricted, or proximal, setting due to the abundance of spores and pollen (including tetrads) as well as the low abundance and diversity of dinoflagellates. These contrasting lines of evidence are not easily reconciled but may reflect high productivity and simple offshore transport of terrestrial palynomorphs.

Evidence across multiple groups (particularly ostracods and foraminifera) recorded from Seavington demonstrates faunal connections to the Iberian-north African region that are not observed in age equivalent records elsewhere in the UK, and these may reflect poleward faunal movement during global climate warming of this period. In addition, recent studies from the early Bifrons Chronozone, Sublevisoni Subchronozone on the Dorset coast note the presence of the ammonite *Leukadiella ionica*, a largely Mediterranean taxon and only the second ever record in the UK (KNP, unpublished data). Other ammonites of Mediterranean affinity recorded at Seavington include *Frechiella* (a relative of *Leukadiella*), *Eodactylites* and early *Polyplectites* (taxa also seen in Morocco).

The microfossils demonstrate a series of extinction events, associated with the T-OAE. The extinction of the Suborder Metacopina (ostracods) at the onset of the CIE is entirely consistent with records elsewhere in northwest Europe (Boomer *et al.* 2008; Cabral *et al.* 2013), with this group disappearing well before the peak of dysaerobia where it is recorded. Decreasing species richness is observed in the foraminifera through the CIE, although some species persist through that period in this section. The nannoplankton are also impacted with the disappearance of species at the top of Bed SM4a, the same level as the disappearance of the Metacopina.

The driving mechanism for extinction is not clear, either at a local level or globally (Remirez & Algeo 2020), but undoubtedly the consequence of hyperthermal conditions associated with the T-OAE led to changes in water-mass structure and its physico-chemical composition, particularly across the northwest European shelf seas (Remirez & Algeo 2020). Müller *et al.* (2020) have provided evidence of ocean acidification at this time through boron stable-isotope analysis of brachiopod shells from the Lusitanian Basin, probably the result of enhanced volcanic activity during the T-OAE. Ocean acidification, alongside warming and dysoxia acted as multi-stress factors that must have contributed to the extinctions noted above. Müller *et al.* (2020) noted a decline in ocean pH through the earliest Toarcian reaching a low immediately prior to the onset of the CIE after which they implied a short period of recovery until minimum values were reached at the peak of the CIE. The microplankton provide no clear evidence for stratification of the water column during the T-OAE although the prevalence of sphaeromorph acritarchs, which are typically associated with the T-OAE regionally, point to some changes in the water column during and immediately after the CIE.

Low sedimentation rates are indicated by the abundant sessile epifauna including serpulids, juvenile oysters and *Nubeculinella*-type encrusting foraminifera that have been observed directly attached to exhumed internal ammonite molds. Evidence of periodic winnowing, possibly associated with ocean shallowing (Krenker *et al.* 2019), is suggested by the concentrations of belemnites in Bed SM2 and possibly by the occurrence of imbricated ammonites in Bed SM5 and other levels with common intraclasts. This may also explain the absence of some of the earliest Toarcian subchronozonal indicator taxa near the base of the exposure.

Summary

The mixed clastic-carbonate section at Seavington provides an internationally important Toarcian succession that reveals a high-quality biostratigraphic data set comprising an unusually rich and diverse ammonite macrofauna with well-preserved microfossil assemblages. The site also provides a clearly documented negative carbon isotope excursion.

Significantly, the foraminifera, and to some extent the ostracods and ammonites, demonstrate affinities to the Iberian Peninsula and North Africa (e.g. Boomer 1992; Herrero 1993a, b; Riegraf *et al.* 1984; Ruget 1982), indicating faunal and palaeoceanographic links between south west England and areas such as Morocco and Spain during the Toarcian, more so than with the East Midlands Platform, Yorkshire and Irish Sea basins (e.g. Copestake & Johnson 2014) to the north and west at this time.

The microfossil and geochemical data demonstrate the local response to the T-OAE, with bottom-water conditions never becoming completely anoxic. These data are significant in a regional context given the relative paucity of age-equivalent sections in the UK with both detailed faunal records and a documented CIE.

Author Contributions

IB: conceptualization (lead), data curation (lead), writing – original draft (lead), writing – review and editing (lead) investigation (lead), formal analysis (lead). **PC:** investigation (supporting), formal analysis (supporting), writing – review and editing (supporting). **KP:** writing – original draft (supporting), formal analysis (supporting). **JH:** writing – review and editing (lead), investigation (supporting). **TL:** writing – original draft (supporting). **PB:** writing – original draft (supporting), writing – review and editing (supporting). **TDJ:** writing – review and editing (supporting). **MO’C:** investigation (supporting). **SH:** investigation (supporting). **DH:** investigation (supporting). **HR:** investigation (supporting). **NC:** investigation (supporting).

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