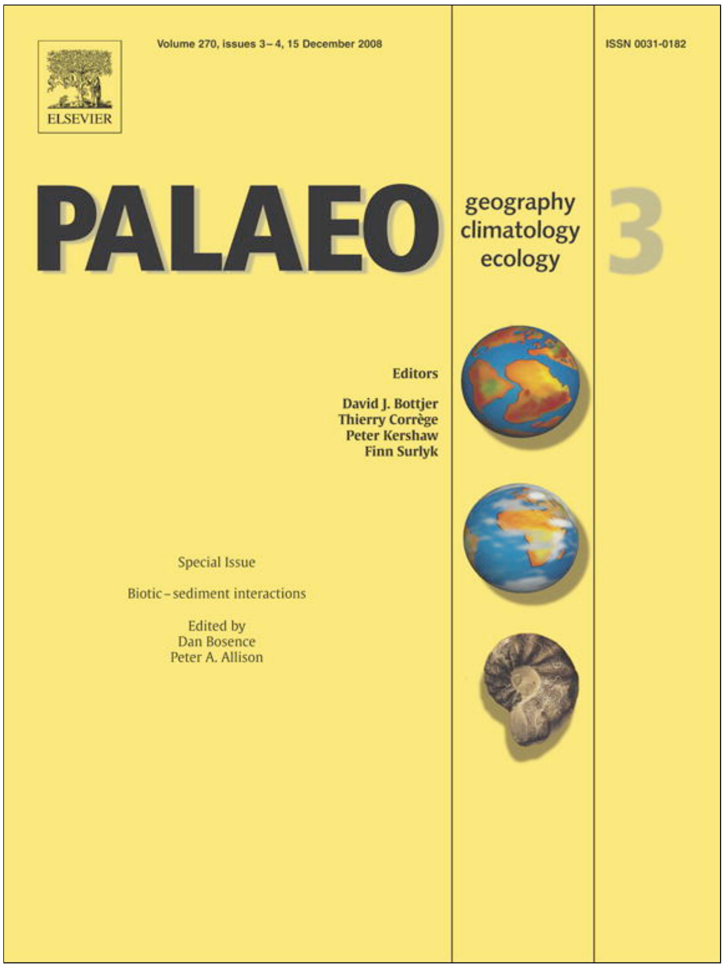

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The occurrence and preservation of ammonites in the Blue Lias Formation (lower Jurassic) of Devon and Dorset, England and their palaeoecological, sedimentological and diagenetic significance

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ABSTRACT

More than two thirds of beds in the lowest Jurassic, Blue Lias Formation lack ammonites, which are commonly preserved in irregular or planar-bedded, bioturbated limestones, very rarely in laminated limestones and almost never in laminated black shales. Ammonites are preserved in 3D in nodular and planar-bedded limestones and at any orientation to bedding. Co-occurrence with macrobenthos and absence from beds without benthos suggest that Blue Lias ammonites were nektobenthonic. Scour structures and imbrication of ammonites in the Best Bed imply presence of traction currents. Lack of epifauna on large cephalopod shells (and other fossils) implies rapid deposition in event beds. Blue Lias deposition was episodic, not slow and continuous as the fine grain size implies. Undistorted trace fossils, uncrushed ammonites and stable isotope values all suggest early cementation of limestone beds from pore waters of a similar composition to contemporary Jurassic sea water. A clear diagenetic trend exists, with limestones having least, and laminated black shales most, modified stable isotope values. Contrast between trace fossil fills and host sediment demonstrates that Blue Lias rhythms are primary, but limestone beds have been diagenetically cemented.

1. Introduction

As part of a wider study of the Blue Lias Formation, Allison et al. (in press) examined two individual limestone beds crowded with ammonites, which they interpreted as concentration lagerstätten. Variations in the preservation and attitude of the ammonites in these beds led us to examine all the beds of the Blue Lias for ammonites, especially as an analysis of Lang's classic paper on the Blue Lias (Lang, 1924) revealed that he recorded ammonites from only 20% of the sedimentary units he recognized. This, in turn, raises the question of whether ammonites occur in the beds as a result of original palaeoecological conditions or as a result of special conditions of preservation. It was soon discovered that the occurrence and preservation of the ammonites (and associated fauna) often reveal at least as much about the palaeoecology, deposition and diagenesis of the Blue Lias as they do about the correlation of the beds, whereas stratigraphic utility is the main characteristic of ammonites in the minds of most palaeontologists.

This paper documents the biostratinomy and diagenesis of the ammonite-bearing beds in the Blue Lias. It also considers the implications of preservation of the ammonites for the paleoecology of the Blue Lias. One would not expect ammonites, which were nektonic, to interact with sediments (the theme of this special issue). Nevertheless, a surprising amount of palaeoecological and sedimentological information can be gleaned from their occurrence and preservation. We believe that the results presented here are of general significance.

1.1. Location

The Blue Lias Formation crops out in several exposures between The Slabs, near Corbin Rocks, Devon and Canary Ledges, Church Bay, Lyme Regis, Dorset (Fig. 1). For this paper we have concentrated our data gathering along the more or less continuously exposed section from the top of the underlying White Lias near the head of Pinhay Bay (National Grid Reference SY3208), round to Seven Rock Point (SY332913), where the topmost part of the section is accessible. Additional data have been derived from other exposures where necessary. The type section is in the railway cutting at Saltford, near Bath, but is now largely obscured (Gallois, 2006). Sections on the north and south coasts of the Bristol Channel are thicker, but locally less accessible and/or complicated by faulting. Although relatively condensed, the section in Pinhay Bay is probably the best continuous section in the Blue Lias Formation in Britain. It lies in Hallam's (1960)

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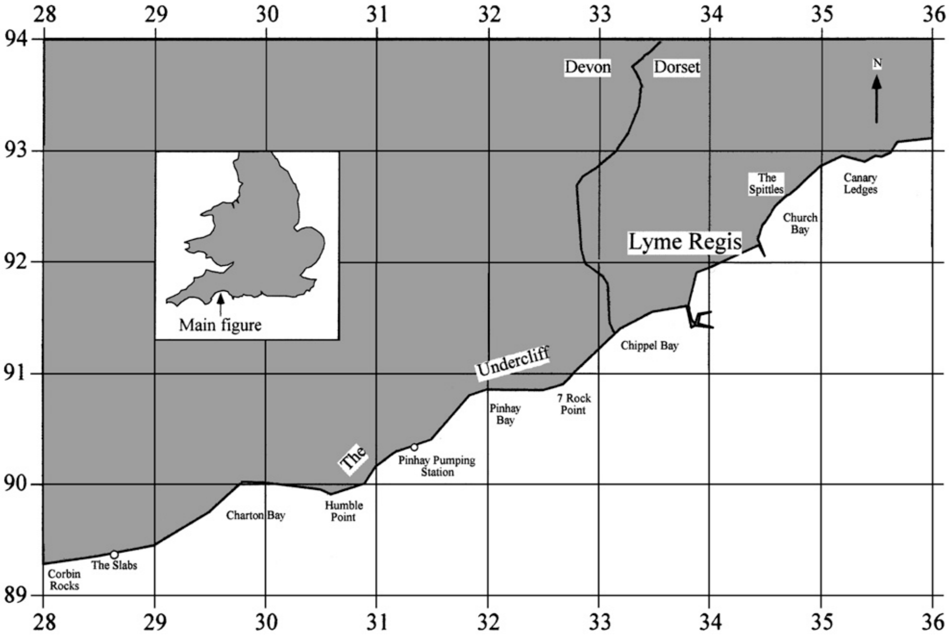


Fig. 1. Outline map showing locations mentioned in the text (scale: 1 km National Grid line spacing).

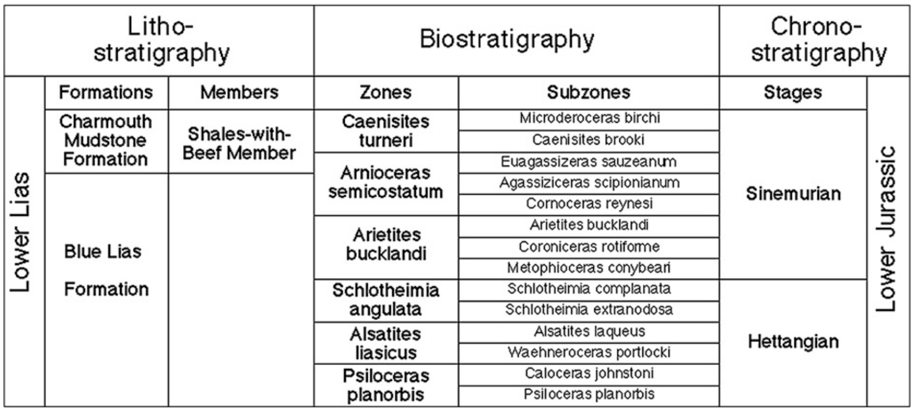
offshore facies and probably represents deeper water than the sections in South Wales. Water depth probably increased up section.

1.2. Stratigraphy

The Blue Lias Formation is currently thought to span the Triassic–Jurassic boundary. At present there is no agreed criterion on which to define the base of the Jurassic (see for example, Hodges, 1994; Warrington et al., 1994; Lucas et al., 2006). However, one of the highest stratigraphic levels proposed coincides with the first appearance of the ammonite *Psiloceras planorbis* (Sowerby). No ammonites are known to occur in the Blue Lias below this level in Britain. As we are principally concerned with ammonite-bearing horizons within the formation, the sections we discuss lie entirely within the lowermost Jurassic. The conventional stratigraphy of the Jurassic part of the formation is shown in Fig. 2.

1.3. Blue Lias Formation

The Blue Lias Formation (Figs. 3 and 4) typically consists of pale grey limestone beds separated by marl and/or shale beds. The limestone beds are typically impure micrite mudstones to wackestones, whereas the more siliciclastic-rich beds in between may include one or more horizons of pale grey calcareous marl, dark grey marl, or laminated black shale (Fig. 5). The last lithology may contain thin (mm scale) layers of beef (fibrous calcite layers). Fossils are generally more common in the limestones than in the more siliciclastic units, especially the laminated black shales. The succession is rhythmic (Fig. 5), with each rhythm having a sharp base overlain by laminated black shale, which usually grades up into dark grey marl, then pale grey marl, commonly with concretionary to tabular micritic limestone, and typically back into dark grey marl before the base of the next rhythm. The rhythms are not always symmetrical and in many cases the only evidence for the upper dark marl is the fill of trace fossils, especially *Rhizocorallium* as shown in Fig. 5, rhythm B. In such cases the laminated black shale rests directly on pale grey marl or limestone. The pale marls may be bioturbated and fossiliferous. In some, but not all, rhythms they are cemented into hard limestone beds, so that the number of limestone beds is significantly lower than the number of sedimentary rhythms (Fig. 4). In the upper part of the formation these hard, ledge-forming limestones were given names by quarrymen in the early 1900s (Fig. 4); for example, bed 19 was called Specketty, in reference to the abundant cross-sections of spar-filled rhynchonellid brachiopods. This bed is well exposed on the foreshore



Litho-stratigraphy			Biostratigraphy		Chrono-stratigraphy	
	Formations	Members	Zones	Subzones	Stages	
Lower Lias	Charmouth Mudstone Formation	Shales-with-Beef Member	Caenisites turneri	Microderoceras birchi	Sinemurian	Lower Jurassic
				Caenisites brooki		
	Blue Lias Formation		Arnioceras semicostatum	Euagassizeras sauzeanum		
				Agassiziceras scipionianum		
				Cornoceras reynesi		
			Arietites bucklandi	Arietites bucklandi		
				Coroniceras rotiforme		
				Metophioceras conybeari		
			Schlotheimia angulata	Schlotheimia complanata	Hettangian	
				Schlotheimia extranodosa		
			Alsatites liasicus	Alsatites laqueus		
				Waehneroceras portlocki		
			Psiloceras planorbis	Caloceras johnstoni		
				Psiloceras planorbis		

Fig. 2. Standard litho-, bio-, and chrono-stratigraphy of the lower part of the Lower Lias in Devon–Dorset, U.K.

Fig. 3. General view of the upper part of the Blue Lias Formation in Church Bay, east of Lyme Regis. Note the alternations of prominent, paler limestone beds and darker 'non-limestone' beds.

on either side of Seven Rock Point. In his classic paper Lang (1924) numbered all the limestone beds as well as the intervening siliciclastic units, but recognized subdivisions of individual beds, especially in the siliciclastic units, where they were formed by more than one lithology. All bed numbers and names used here follow Lang (1924).

Three types of limestone facies occur, two of which, nodular and laminated (Fig. 6), have previously been recognized in Dorset (Lang, 1924; Hallam, 1960). Nodular limestones have uneven surfaces, especially the upper surfaces, are thoroughly bioturbated and richly fossiliferous. They frequently have fossils preserved in situ (Fig. 7) and in apparently random and unstable orientations (Fig. 8). Beds H40–H44 are good examples and Lang (1924) drew attention to the uneven surface in his Bed 23, Mongrel. Laminated limestones (Fig. 6) have planar upper and lower surfaces and clear internal laminations (mm scale) or thin (cm scale) beds. They are sparsely fossiliferous. Beds H32–H38 are excellent examples (Fig. 6). The third facies we recognize consists of planar-bedded limestones. These limestones have generally planar surfaces, but lack internal laminations or bedding, being thoroughly mixed. Their surfaces resemble those of laminated limestones, but internally they are very similar to the nodular limestones, especially in having apparently randomly or unstably orientated fossils. Best Bed, 41 (Fig. 9) is probably the best example of this facies, but most of the limestones above bed 33 (Gumption) fall into this category.

2. Methods

2.1. Field

Each individual bed recognized by Lang (1924), as well as subdivisions of Lang's beds where we recognized further subtleties of sedimentation, were searched for ammonites in cross-sections in the cliffs from the head of Pinhay Bay (National Grid Reference SY32029084), round Seven Rock Point to Chippel Bay (SY33209138). Additional information was also gathered from sections at The Slabs (SY286894) and on the west side of Pinhay Bay from below the Pinhay Pumping Station (SY31309034 to SY31519043). The lithology of, and the time taken to examine each bed were recorded. Important examples of fossil preservation were photographed in situ or in loose blocks on the foreshore and specimens collected if at all possible.

For stable isotope analysis two profiles in Chippel Bay were sampled from the top of Specketty (bed 19) through Second Mongrel (bed 21) into the base of Mongrel (bed 23). The two profiles were 1 m apart horizontally. One profile passed through bed 21 where it is entirely marl, the other through a concretion in the middle of it (Fig. 10).

2.2. Laboratory

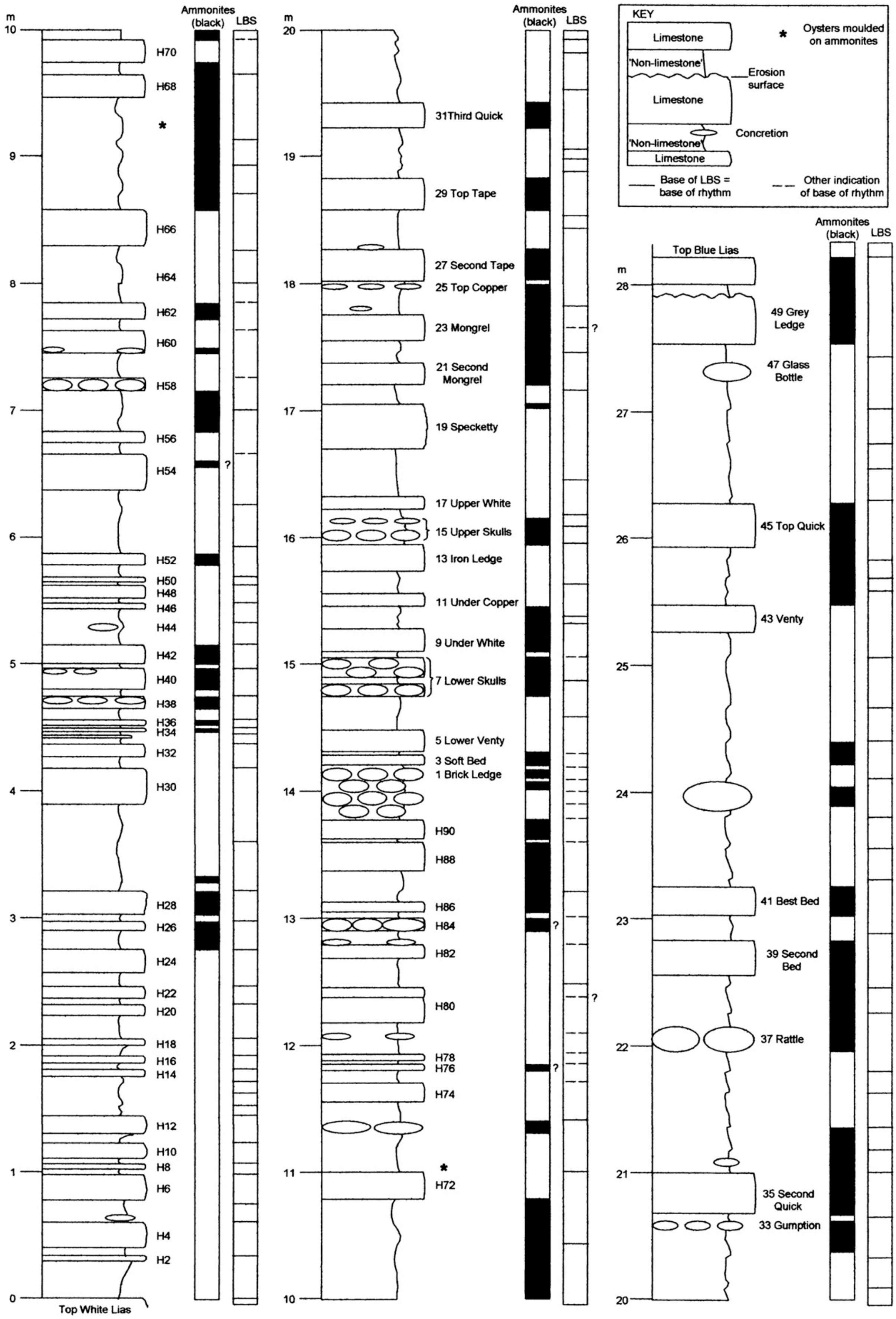
All samples for stable isotope analysis were dried overnight in an oven before further preparation. Small subsamples were then ground to powder using a dental drill, thus all data relate to bulk rock chemistry. Acid insoluble residue (AIR) values were determined by dissolving a weighed amount of powder in an excess of hydrochloric acid and then washing, filtering, drying and weighing the residue. Approximately 3 mg of the powders were used to determine stable isotope values of carbon and oxygen in the Liverpool University Stable Isotope Laboratory. All samples were roasted in a low-pressure plasma oven for 4 h to remove any organic matter. Gaseous CO_2 for analysis was released by reacting the powder with 2 ml anhydrous 100% orthophosphoric acid in a constant temperature bath at 50 °C for at least 3 h or until the reaction was complete. An acid fractionation factor of 1.00928 was used (Friedman and O'Neil, 1977). All samples were calibrated using NBS 19 and are expressed as per mil (‰) variation relative to the VPDB (Vienna Pee Dee Belemnite) standard. Sample reproducibilities are better than 0.1‰ for both oxygen and carbon isotopic values.

3. Results

3.1. Stable isotopes

Stable isotope and acid insoluble residue values are given in Table 1, summarized in Table 2 and the curves depicted in Fig. 10. Laminated black shales have the most negative isotope values for both carbon and oxygen and the highest insoluble residue values; limestones the least negative stable isotope values and lowest insoluble residue values. Pale marls have intermediate values for all three. A cross-plot of carbon versus oxygen values (Fig. 11A) shows a strong correlation and hence a clear diagenetic trend. There is also a reasonable differentiation by lithology. Equally, plots of both carbon and oxygen against insoluble

Fig. 4. Summary, simplified lithological log of the Blue Lias Formation in Devon–Dorset (largely based on the exposures in Pinhay Bay), to show Lang's (1924) bed numbers and names, levels where ammonites have been recorded (black) and bases of laminated black shale (LBS) horizons (or other indications of the bases of sedimentary rhythms). Note that frequent, substantial intervals without ammonites occur and that the number of inferred rhythms (111–113) considerably exceeds the number of limestone beds (77–84). 'Non-limestone' beds include any or all of the following more siliciclastic-rich lithologies; pale marl, dark marl or laminated black shale.


KEY
Limestone
'Non-limestone'
Erosion surface
Limestone
Concretion
'Non-limestone'
Limestone
*
Oysters moulded on ammonites
Base of LBS = base of rhythm
Other indication of base of rhythm
m
Ammonites (black)
LBS
Top White Lias
0
1
2
3
4
5
6
7
8
9
10
H2
H4
H6
H8
H10
H12
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H80
H82
H84
H86
H88
H90
1 Brick Ledge
3 Soft Bed
5 Lower Venty
7 Lower Skulls
9 Under White
11 Under Copper
13 Iron Ledge
15 Upper Skulls
17 Upper White
19 Specketty
21 Second Mongrel
23 Mongrel
25 Top Copper
27 Second Tape
29 Top Tape
31Third Quick
20
21
22
23
24
25
26
27
28
33 Gumption
35 Second Quick
37 Rattle
39 Second Bed
41 Best Bed
43 Venty
45 Top Quick
47 Glass Bottle
49 Grey Ledge
Top Blue Lias

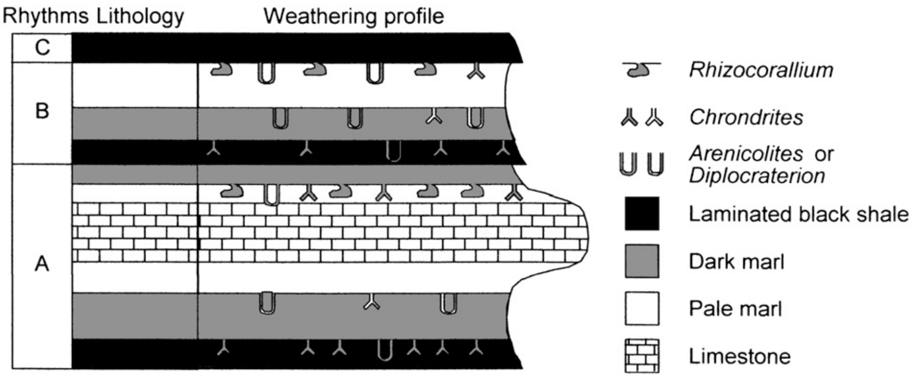

Fig. 5. Idealized Blue Lias rhythms showing principal lithofacies. In rhythm A the pale marl horizon has been diagenetically cemented into a limestone bed and is overlain by a dark marl bed. In rhythm B the pale marl remains uncemented and the overlying dark marl has been eroded away. Its former presence is indicated by the dark marl fills of trace fossils penetrating the top of the pale marl. Trace fossils purely schematic; a greater variety is recorded from the Blue Lias.

residue values (Fig. 11B) show an excellent correlation ($r = 0.745$ for δ^{13}C and 0.755 for δ^{18}O, both of which are significant at <0.1%).

3.2. Occurrence of ammonites

Table 3 shows the number of beds from which ammonites have been recorded in the Blue Lias Formation of Devon and Dorset as documented by Lang (1924), by recent recording of the authors, and the combined total. The zonal scheme is taken from Dean et al. (1961) and the beds included in each zone from Cope et al. (1980). Where Lang (1924) subdivided beds, we have treated each subdivision as a separate bed. Unlike Palmer (1972), who recommended a thorough revision of Lang's lithostratigraphical divisions, we have found very little difficulty in recognizing all the subdivisions in Lang's very detailed succession. Occasionally Lang recorded ammonites from a thick bed and also from a subdivision of the same bed. In such cases it is uncertain whether or not the two records came from the same horizon, so numbers in parentheses (Table 3, columns 4, 6 and 7) indicate the maximum possible number of beds yielding ammonites. In some subzones our recording merely confirmed Lang's (1924) records (e.g., the Bucklandi subzone); in others our records are additional to Lang's (e.g., the Portlocki and Laqueus subzones). The 'combined' column in Table 3 records all beds from which ammonites have so far been recorded by Lang (1924) and ourselves and shows that over two thirds of the beds have not yielded ammonites to date. Fig. 4 shows a graphic summary of the occurrence of ammonites throughout the Blue Lias, but is too general to illustrate the details of each individual bed.

In the lower parts of the formation ammonites are associated with a diverse fauna of bivalves, echinoderms and brachiopods. They predominantly occur, often with bivalves such as *Pleuromya* preserved in life position (Fig. 7), in nodular limestone beds (Fig. 6). Laminated limestones, in which the limestone beds are planar and have internal laminations, are generally unfossiliferous (Fig. 6). This distinction is not absolute and we have recorded three small ammonites in bed H36 in the laminated limestone facies. The distinction between laminated and nodular limestones becomes less obvious, and ammonites generally more common, up section. In the Sinemurian part of the formation, laminated limestones are uncommon and replaced by planar-bedded limestones. Table 4 contrasts the generic diversity of body fossils in laminated versus nodular facies of the lower part of the Blue Lias Formation (beds H24–H78), as well as contrasting the faunal diversity in beds with and without ammonites. Maximum and minimum diversity are distinguished due to the difficulty of identifying some fossils seen only as cross-sections in limestone beds. Mean generic diversity of beds with ammonites is twice that of beds without ammonites, whereas mean generic diversity of nodular facies is nearly ten times that of the laminated facies (Table 4). In addition, especially lower in the succession, limestones of the nodular and laminated facies are bundled together, as first noted by Hallam (1960). So, for example, Lang's beds H24–H28 are all in nodular limestone facies, whereas H32–H36 are laminated limestone facies. Then H38–H44 are nodular limestone facies again. This means that not only are ammonites present in a minority of beds, but that significant ammonite-free intervals occur (Fig. 4). This bundling of facies also becomes less obvious up section.

In our experience ammonites are more common in the pale marl and limestone beds, than in dark marls. We have very rarely seen ammonites preserved in laminated black shale beds. Lang (1924) did not distinguish the four types of beds we recognize (Fig. 5). However, he recorded ammonites in more (24) 'non-limestone' layers than limestone beds (15). This may reflect different recording techniques. Except where he repeated earlier published records from survey memoirs (Woodward, 1893, 1906, 1911), all Lang's records were for specimens collected and now conserved in the Natural History Museum, London. Our records are predominantly from cross-sections through beds in the cliffs. Uncrushed ammonites are much easier to spot in limestone beds than crushed ammonites in 'non-limestone' layers.

3.3. Preservation

In general ammonites preserved in marl beds are crushed, with or without the shell remaining. Ammonites in laminated limestones are also compressed in some cases (Fig. 12). Crushed ammonites are more or less inevitably preserved parallel to bedding due to the degree of compaction of the sediments. Ammonites in nodular and planar bedded facies limestones are generally uncrushed (Fig. 8), commonly with spar-filled chambers (Fig. 9A), or in larger examples with dog-tooth spar linings to chambers (Fig. 13) and are frequently found preserved in random orientations with respect to bedding (Figs. 8C, 9A, 16B). In particular, Best Bed (bed 41) is locally crowded with small (up to 5 cm diameter), spar-filled, apparently randomly orientated ammonites (Fig. 9A), but sometimes imbricated (Fig. 9C). As Hallam (1960) observed, vertically-preserved ammonites are not uncommon, but usually small. The largest we have seen was at least 17 cm across (Fig. 14), but most are 5 cm or less. However, we have also seen large nautiloids up to 30 cm across preserved vertical to bedding (Fig. 15), although their flattened venter makes this position more stable for nautiloids than for ammonites. Nevertheless, ammonites are not the only fossils to be preserved in unexpected orientations. Single valves of bivalves, including planar valves of oysters, have been recorded preserved vertically (and at other orientations) in nodular facies limestones (e.g., see shells in Figs. 8C and 13). *Pinna*, *Pleuromya* (Fig. 7) and *Gryphaea* are not infrequently preserved as paired valves in life position, but isolated valves of almost all bivalve genera have been found randomly orientated in nodular facies limestones. Top Tape

Fig. 6. General view of the alternation of bundles of nodular limestone facies and laminated limestone facies in the lower Blue Lias Formation, from bed H30 up to H58, Pinhay Bay, (National Grid Reference [NGR] SY32189084).

(bed 29) is crowded with ammonites, which sometimes have different sediment filling chambers than the host sediment (e.g., compare Fig. 13 with Fig. 16A). Allison et al. (in press) record densities of up to nine ammonites per m^2 and interpret this level as a condensed bed.

In summary, ammonites occur in a small proportion of beds within the Blue Lias Formation. In only three beds are they really common. They mostly occur in nodular and planar-bedded facies limestones and, due to the bundling of facies, significant gaps occur in the ammonite fossil record. Ammonites in ‘non-limestone’ layers and laminated limestones are typically crushed and parallel to bedding. Those preserved in nodular and planar-bedded facies limestones are typically uncrushed, spar-filled, and preserved in random orientations with respect to bedding, as are other tabular fossils, such as isolated valves of bivalve molluscs. These observations on the ammonites have a bearing on the palaeoecology of the ammonites, the deposition and diagenesis of the sediments (and fossils), and the origin of the rhythmic bedding in the Blue Lias. Each of these points will be discussed in turn.

4. Interpretation

4.1. Palaeoecology

Most Blue Lias ammonites, except ?*Charmasseiceras*, are evolute to strongly evolute (e.g. Figs. 9A, 12 and 14), with extensive body chambers. From Trueman's classic study on life orientation of ammonites (Trueman, 1941) it is unlikely that they were strong swimmers, or typical of open-water habitats. They co-occur with obvious benthos, especially in nodular facies limestones, where bivalves such as *Pleuromya* or *Gryphaea* are preserved in life position. However, they are generally absent from all beds where benthos is also absent, including laminated limestone facies and laminated black shales. This correlation with benthos suggests that they were nektobenthic rather than pelagic. Shells floating in open oceans might be expected to have been preserved independent of facies. Blue Lias ?*Charmasseiceras* are generally large, fairly involute ammonites, typical of Lang's (1924) beds 25, 27, 29 (e.g. Fig. 13) and 31. They may have been better swimmers, but there is still no evidence of preservation independent of obvious benthos.

Fig. 7. *Pleuromya* in life position in the top of a nodular facies limestone bed H40, Pinhay Bay, (NGR, SY32269084). Chisel shaft is 12.5 mm in diameter.

4.2. Deposition of the Blue Lias

All the sediments are fine-grained, predominantly clay grade, containing varying proportions of siliciclastic clay minerals and micrite. Visible fossil constituents form a small proportion of the limestone beds, but generally become rarer up section. Some nodular facies limestone beds can be described as shelly limestones (skeletal wackestones), but most are micrite mudstones. Lang's bed H30 (Fig. 6) is a structureless, microcrystalline limestone of lithographic stone quality, with just 4% acid insoluble residue (Hallam, 1960). With such fine-grained sediments one naturally assumes the primary mechanism of deposition was settling from suspension, and in some of the laminated black shales and laminated limestone beds this may well have been the case. In such a model the laminated sediments represent deposition without any subsequent disturbance, either by physical or biological reworking. The water depth was presumably well below storm wave base and, at least for laminated black shales, it is usually assumed that bottom waters were anoxic, thus preventing colonization by infaunal and epifaunal benthos (Moghadam and Paul, 2000; Martin, 2004). The nodular and planar-bedded facies limestones are assumed to have been thoroughly mixed by bioturbation and therefore to represent oxygenated bottom conditions allowing infauna and macrobenthos to colonize the sea floor. Bioturbation is the usual explanation for the occurrence of fossils in unstable and apparently random orientations. Blue Lias rhythms then represent redox cycles in a quiet environment.

There are, however, some problems with the above simple model. For example, Martin (2004) reported scour structures and Allison et al. (in press) the presence of exotic sediments filling ammonite chambers and trace fossils, which are not detectable in the section as separate beds. These features imply erosion or sedimentation from strong lateral traction currents and hence significant reworking of the sediments after initial deposition. Best Bed (41) is perhaps the most dramatic example. It is a complex bed with a paler lower mudstone unit, overlain by a darker floatstone to rudstone unit, which contains patches of small, densely packed ammonites that are apparently randomly orientated (Fig. 9A), but are locally imbricated (Fig. 9C). It is also locally graded (Fig. 9B), and gives the impression that the ammonite-bearing, upper part was dumped out of suspension in a very short time.

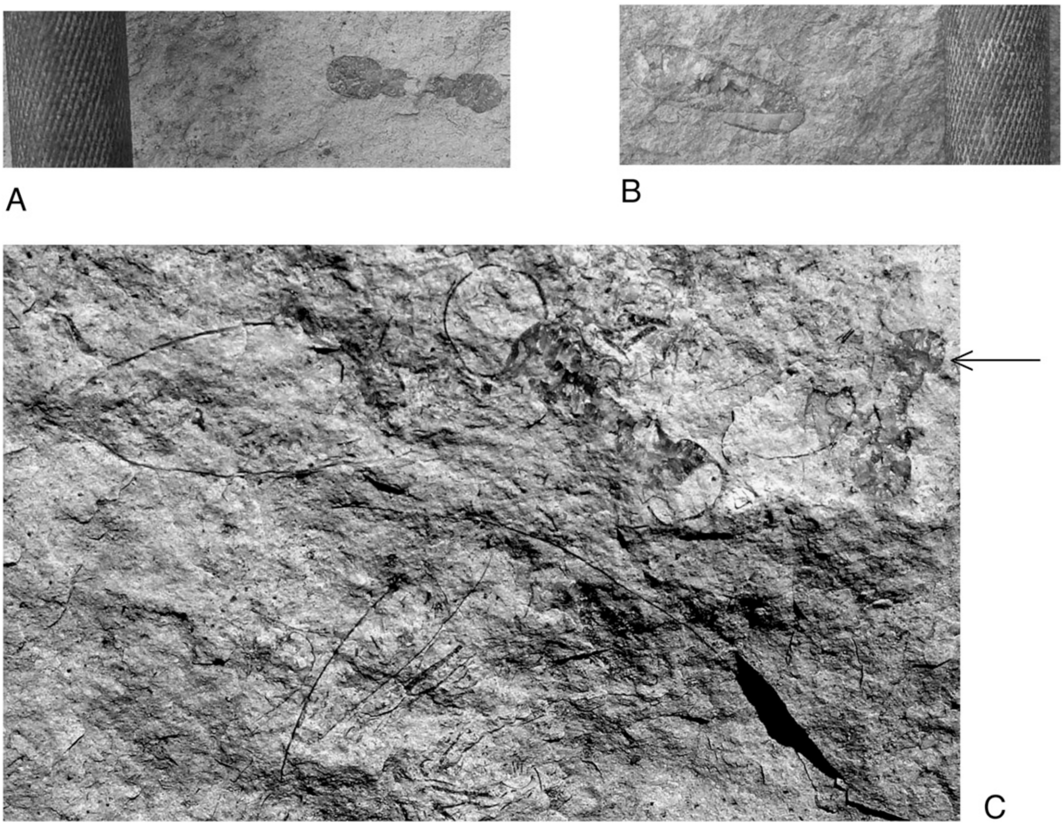

Fig. 8. Uncrushed ammonites exposed on joint surfaces of nodular facies limestones. (A) A nearly horizontal *Caloceras*, Bed H 38 (NGR SY32229084). (B) *Psiloceras* with geopetal infill, bed H28 (NGR SY32139084). (C) Two *Caloceras* (top right) at circa 45 and 90° (arrow) to bedding, bed H42 (NGR SY32259084). Note the unstably orientated bivalve debris. Shaft of chisel 12.5 mm across. All Pinhay Bay.

Curtis et al. (2000) have described assemblages of ammonites from concretions higher in the Lower Lias, which often preserve remains of jaw structures and many of which are preserved oblique to bedding 'either as pods, stringers or scattered individuals' Curtis et al., 2000, p. 166). These occur 'uncrushed in thinly-bedded (0.001 m) peloidal sediments associated with small-scale upwards fining couplets.' (Curtis et al., 2000, p. 165). They interpreted the ammonite associations as 'life assemblages' due to the preservation of jaws, and the sedimentation as 'instantaneous' due to the fining-up beds, which they suggested were deposited from waning currents after resuspension. Lack of benthos and bioturbation enabled preservation of not only of the fining-upwards sedimentary structures, but also the peloidal nature of the original sediments. Bed H50 is laminated with several thin, fining-upwards layers and resembles the sediments Curtis et al. (2000) described. It seems possible that the nodular and planar-bedded facies limestones were deposited in a similar manner, but the original laminations and peloidal structure, which would be necessary for sediment resuspension, have been destroyed by subsequent bioturbation.

Gallois (2006) considered the sharp bases of many of the laminated black shale beds as erosional features. The frequent removal of the underlying dark marl (Fig. 5, rhythm B) and the common occurrence of concentrations of echinoderm debris and of isolated oyster valves in laminated black shales all tend to support this view. Thus we believe there is abundant evidence for erosion by, and deposition from, traction currents within the Blue Lias of Devon and Dorset, rather than just passive settling from suspension.

The second problem concerns the oysters in laminated black shales. Although these beds are generally unfossiliferous and unbioturbated, individual oyster shells do occur not uncommonly. For example, we have recorded oysters in twelve laminated black shale beds between H1 and H55 inclusive. We have found oysters moulded over ammonites in two laminated black shale beds and Lang (1924) reported other examples. It is possible that these oysters attached to the ammonite shells while they were still floating. When they settled to the sea floor the aragonitic ammonites dissolved, leaving the calcitic oysters as the only evidence of their former existence. Nevertheless, the vast majority of oysters found in laminated black shales show no evidence of having been attached to something that might have floated. Their occurrence in undisturbed, laminated sediments that are supposed to indicate anoxic bottom waters is puzzling, unless brought in from elsewhere by currents.

The next problem concerns the rate of sedimentation and burial of fossils. Even assuming that the entire Blue Lias is of Jurassic age, this gives just under 18 m of section in the Hettangian, which lasted at least 3 million years (Cope et al., 1980), and implies an average sedimentation rate of 6 mm per thousand years (ky). At that rate it would take 10 ky to bury a horizontal ammonite shell 6 cm thick. The nautiloids cause even bigger problems. They reach 30 cm in diameter by up to 17 cm maximum width and are frequently preserved vertically (Fig. 15). A 24 cm high, vertically orientated nautiloid would take over 40 ky to become completely buried. An alternative approach is to assume that each rhythm represents the 20 ky precession cycle. We recognize 113 rhythms in approximately 28 m of section. This gives an average thickness of 24.78 cm per rhythm and corresponds to a sedimentation rate of 12.39 mm per ky. At that rate it would take half as long to bury large ammonites or nautiloids, but it is impossible to imagine an aragonitic shell exposed on the sea floor for even 5 ky without gaining any encrusting epifauna or indeed the shell dissolving away completely. The bivalve *Pinna* had a calcitic shell and was semi-infaunal in life. We have seen examples of *Pinna* in life position in Bed H42, but truncated at the inferred top of the limestone bed, suggesting that even exposed

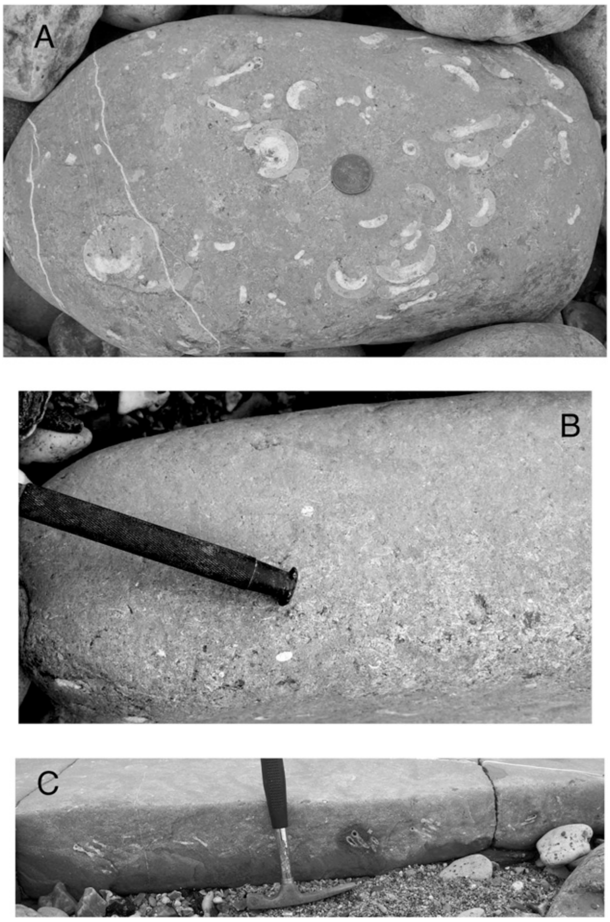

Fig. 9. Two loose blocks of Best Bed (41) showing, (A) randomly orientated, spar-filled, small ammonites and (B) graded bedding. Both Chippel Bay, (NGR SY331912). (C) Imbricated ammonites in joint surface of Best Bed, The Slabs, (NGR SY286894). Coin is 25 mm across (A). Chisel shaft is 12.5 mm across (B). Hammer head is 18 cm long (C).

Table 1
Stable isotope (‰ VPDB) and acid insoluble residue values (AIR) from beds 19–23, Blue Lias Formation, Chippel Bay, Lyme Regis

Sample no.	Elevation*	$\delta^{13}C$	$\delta^{18}O$	AIR %	Rock type
1	−1	−1.220	−4.421	18.53	Limestone
2	1	−1.036	−4.206	42.00	Pale marl
3	10	−1.557	−4.427	56.26	Pale marl
4	20	−1.235	−4.613	43.47	Pale marl
5	30	−1.167	−4.542	52.39	Pale marl
6	36	−1.668	−5.616	59.55	Pale marl
7	38	−1.775	−5.777	61.47	Laminated black shale
8	40	−1.534	−5.123	61.58	Laminated black shale
9	46	−1.193	−4.227	35.26	Pale marl
10	48	−0.536	−4.416		Limestone
11	55	−0.715	−2.766		Limestone
12	66	−0.523	−3.004		Limestone
21	−1	−1.191	−4.568	17.66	Limestone
22	1	−0.937	−4.093	44.48	Pale marl
23	10	−1.869	−5.114	57.29	Pale marl
24	19	−1.058	−4.393	45.28	Pale marl
25	20	−1.127	−4.764	33.99	Limestone
26	25	−0.689	−3.164	13.51	Limestone
27	29	−0.952	−3.773	26.55	Limestone
28	30	−1.070	−4.110	47.19	Pale marl
29	36	−1.084	−4.767	61.28	Pale marl
30	38	−1.906	−5.422	70.24	Laminated black shale
31	43	−1.601	−4.401	53.10	Laminated black shale
32	48	−0.689	−3.088	16.41	Limestone

*Elevation in cm above or below the top of bed 19. VPDB = Vienna Pee Dee Belemnite international standard.

calcite fossils did not survive long unless buried within the sediments, which in turn were probably rapidly cemented. Ammonites with encrusting epifauna that could have grown while the ammonite shell was exposed on the sea floor are rare. Examples up to 30 cm diameter and almost completely encrusted with oysters occur in Bed H68, and small crushed ammonites with epifaunal oysters occur on the top surface of the limestone bed above bed 49 (Fig. 12), but we have not seen them at any other horizon. Epifaunal oysters on nautiloid shells are even rarer; one possible example has been seen in bed H72. The simplest explanation of the lack of encrusting organisms is that most large

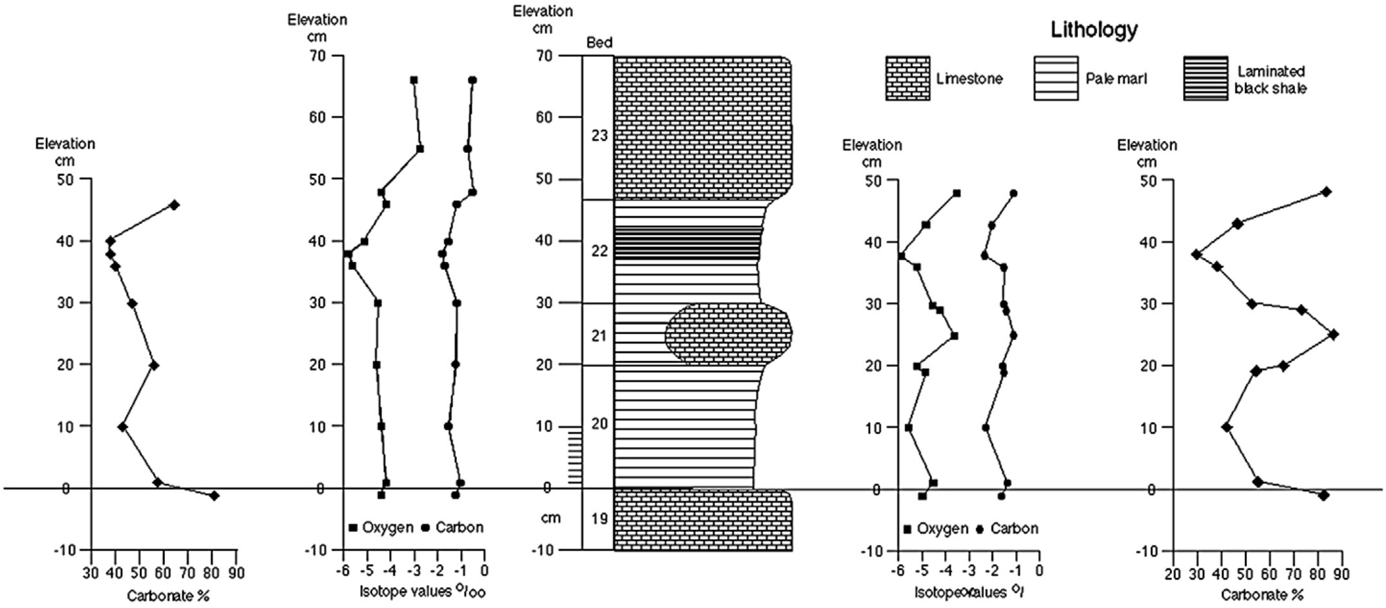

Fig. 10. Two profiles for isotope and insoluble residue samples taken through Lang's beds 19–23 in Chippel Bay, (NGR SY33009124), with results. Curves to the left relate to the profile without the concretion in bed 21; those to the right relate to the profile through the concretion. Note that in both profiles the most negative oxygen isotope values come from the laminated black shales and the least negative from the limestones.

Table 2
Mean stable isotope (‰ VPDB) and acid insoluble residue values (AIR) by lithology, beds 19–23, Blue Lias Formation, Chippel Bay, Lyme Regis

Rock type	Mean δ^{13}C	Range	Mean δ^{18}O	Range	Mean AIR %	Range	Mean carbonate %	Range
A. All samples								
Laminated black shale	−1.704 (*n*=4)	−1.906 to −1.534	−5.188 (*n*=4)	−5.777 to −4.401	61.60 (*n*=4)	53.1 to 70.2	38.40 (*n*=4)	29.8 to 46.9
Pale marl	−1.261 (*n*=11)	−1.668 to −0.937	−4.767 (*n*=11)	−5.616 to −4.093	49.50 (*n*=11)	35.3 to 61.6	50.50 (*n*=11)	38.4 to 64.7
Limestone	−0.849 (*n*=9)	−1.220 to −0.523	−3.774 (*n*=9)	−4.764 to −2.766	21.11 (*n*=6)	13.5 to 34.0	78.89 (*n*=6)	66.0 to 86.5
B. Concretionary level only								
Pale marl (samples 4, 5)	−1.201 (*n*=2)	−1.235 to −1.167	−4.578 (*n*=2)	−4.613 to −4.452	47.93 (*n*=2)	43.5 to 52.4	52.07 (*n*=2)	47.6 to 56.5
Concretion (samples 25–27)	−0.923 (*n*=3)	−1.127 to −0.689	−3.900 (*n*=3)	−4.764 to −3.164	24.68 (*n*=3)	13.5 to 34.0	75.32 (*n*=3)	66.0 to 86.5

VPDB=Vienna Pee Dee Belemnite international standard.

cephalopod shells were buried rapidly, before any encrusting epifauna could become established. The alternative, that large cephalopod shells lay on the sea floor in anoxic conditions, which precluded encrusting organisms would invalidate the argument that thoroughly mixed beds were caused by intense or prolonged bioturbation, since large ammonites and nautiloids occur in nodular or planar-bedded limestones. Furthermore, even in anoxic conditions that would preclude encrusting epifauna, aragonitic shells would not last very long exposed on the sea floor. The conclusion that limestone beds with large ammonites or nautiloids in them were deposited very rapidly seems inescapable. This, in turn, implies even slower average sedimentation rates for those beds without any evidence of rapid accumulation.

The occurrence of some of the fossils in unstable orientations is also potentially a problem for the idea that such orientations arise from intense or prolonged bioturbation. Fig. 14 shows a vertical ammonite, 17 cm across, with sediment filled chambers at the base of bed 31. The fact that the chambers are filled with sediment strongly suggests that the shell was not still partly gas-filled and assumed a vertical orientation by buoyancy on reaching the sea floor. If it fell over on one side, what bioturbating organism was able to reorientate it into a vertical position, especially if it was even partly buried in sediment? If it was deposited in a vertical orientation, then as with large nautiloids, it must have been buried very rapidly since it lacks epifauna and is not truncated. Even smaller, thinner shells, such as the remains of many oysters and other bivalves (e.g., Figs. 8B and 13) appear too delicate to withstand the stresses involved in reorientation within stiff sediment.

Consideration of which organisms might have thoroughly bioturbated the limestone beds and produced observed unstable orientations also raises problems. There were no infaunal echinoids in Hettangian times (Barras, 2006). The bivalve *Pinna* was semi-infaunal, byssally attached (Cox et al., 1969) and did not move. *Pleuromya* and *Pholadomya* have large pallial sinuses (Cox et al., 1969) and were deep burrowers, but may well have remained immobile, like the modern *Mya*. The largest of the trace fossils is *Thallasinoides*, which was probably formed by a small, shrimp-like crustacean. However it has burrows only 5–6 cm across and from *Thalassinoides* burrows preserved below hardground surfaces, it is known that the *Thalassinoides* organisms excavated around obstacles, they did not move them (e.g., Jarvis and Woodroof, 1984). Thus although there is plenty of evidence of bioturbation and of undoubted infaunal organisms, reorientation of the largest and most delicate fossils by bioturbation is difficult to accept.

Sheppard et al. (2006) have interpreted as omission surfaces the upper surfaces of 44 out of 82 limestone beds in the Bucklandi and lower Semicostatum zones of the Blue Lias of Glamorgan. They describe some features similar to those we have seen in the Blue Lias of Devon and Dorset. In particular, they mention randomly orientated and clustered *Gryphaea* and dislodged specimens of the bivalve *Pinna* bearing encrusting epifauna. Significantly, they also describe hummocky cross-stratification in some of the higher beds in their section, whereas we have seen only one dubious example of this storm-induced sedimentary structure. Sheppard et al. (2006) also describe shell lags and other features absent from the Blue Lias of Devon and Dorset and we are unsure how much the two sections are directly comparable. Certainly the Welsh succession was frequently above storm wave base, whereas that in Devon and Dorset seems not to have been.

The occurrence of bivalves in life position in many nodular facies limestones, demonstrates that after final deposition some beds remained stable for considerable periods. Such sediment layers may have been deposited rapidly, but ultimately they were left intact and available for colonization by burrowing infauna. This evidence points to another important aspect of the limestone layers; following their

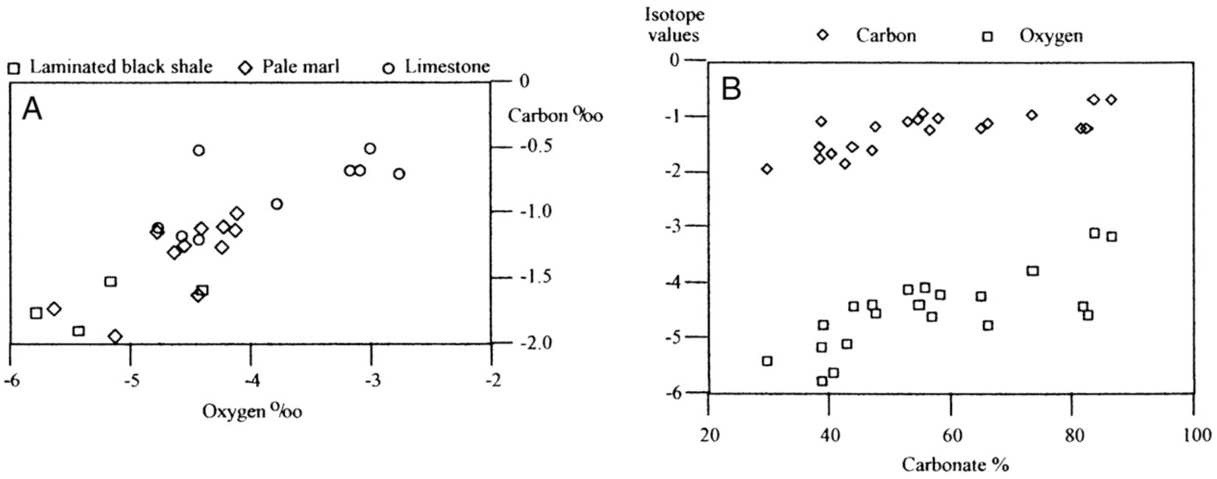

Fig. 11. (A) Cross plot of oxygen versus carbon isotope values. Note the diagenetic trend with limestones having least negative, and laminated black shales most negative, values for both isotopes. (B) Plot of oxygen and carbon isotope values against insoluble residue values. Note clear trends with most negative values for both isotopes correlated with least carbonate content.

Table 3
Proportion of beds in the Blue Lias Formation known to yield ammonites

Beds yielding ammonites						
Subzone	Bed numbers	Total number of beds	Lang	This paper	Combined	Percentage
C. reynesi	47–49	3	3	3	3	100
A. bucklandi	41–46	23	7 (8)	2	7 (8)	30 (35)
C. rotiforme	30–40	40	5 (7)	2	7 (9)	18 (23)
V. conybeari	21–29	18	4 (5)	5	5 (6)	28 (33)
S. complanata+ *S. extranodosa*	H84–20	48	8	5	11 (13)	23 (27)
A. laqueus	H69–H83	15	2	2	4	27
W. portlocki	H57–H68	15	5	2	7	47
C. johnstoni	H43–H56	14	2	3	4	27
P. planorbis	H24–H42	19	3	7	9	47
Totals		195	39 (43)	31	57 (63)	29 (32)

Fig. 12. Crushed ammonite (?*Arnioceras*) with epifaunal oysters in the laminated limestone facies, top surface of the bed above bed 49 (Grey Ledge), below Pinhay Pumping Station, (NGR SY313903). Visible part of the tape measure is 5 cm across.

typically rapid deposition, they remained close to the sediment–water interface for prolonged periods of time. However, the lack of hardgrounds indicates they were rarely, if ever, exposed at the sediment–water interface. Blue Lias sedimentation was episodic, not quiet and continuous as the fine grain size might suggest.

4.3. Diagenesis

4.3.1. Lithification and compaction

Even in marls and laminated limestones where the ammonites are typically crushed, the aragonitic shells survived long enough to leave an impression in the sediment. Ammonites with epifaunal bivalves are not uncommon in beds H68 and the limestone bed above bed 49, and the epifauna may have enhanced the chances of preservation and recording (e.g., Fig. 12). For example, Lang (1924) records a specimen of *Ostrea irregularis* (Münster) forming a natural mould of *Psiloceras* from bed H25. Even chambered shells were of insufficient strength to resist compaction due to burial for long. However, ammonites in limestones, especially nodular and planar-bedded facies limestones, are typically uncrushed (Figs. 8, 9, 13, and 16A). Pyrite linings to chambers do occur, but are not confined to inner whorls or small specimens. One of the largest ammonites we have seen (>55 cm across at the beginning of the body chamber) preserved on the under side of a loose block of Grey Ledge (Bed 49) had pyrite linings to both chambers and body whorl (Fig. 17). Although many ammonites preserved in limestones possess spar-filled chambers, the spar is almost certainly late, deep burial, diagenetic cement. Curtis at al. (2000) record little or no early cements in closed ammonite chambers, but significant volumes of deeper burial cements. It seems likely that neither rare pyrite linings nor early diagenetic cement linings were the cause of three-dimensional preservation of ammonites in limestone beds. Rather we think this was due to early cementation of the limestones before significant compaction occurred. Thus the pyrite linings and spar fills were able to form because the uncrushed ammonite chambers preserved suitable voids in which these minerals could be precipitated later. Evidence to support this comes from trace fossils and stable isotopes. Vertical cross-sections of horizontal

Table 4
Generic body fossil diversity of limestone beds in nodular and laminated limestone facies of the lower part of the Blue Lias Formation

Bed number	Minimum diversity	Maximum diversity	Limestone facies
H24[a]	8	9	Nodular
H26[a]	8	8	Nodular
H28[a]	7	8	Nodular
H30	0	0	Laminated
H32	0	0	Laminated
H34	0	0	Laminated
H36[a]	2	2	Laminated
H38[a]	5	5	Nodular
H40[a]	9	9	Nodular
H42[a]	7	7	Nodular
H44[a]	11	11	Nodular
H46	1	1	Laminated
H48	2	2	Laminated
H50	0	0	Laminated
H52[a]	3	3	Laminated
H54[a]	11	12	Nodular
H56	6	9	Nodular
H58	6	8	Nodular
H60[a]	5	6	Nodular
H62	4	4	Nodular
H64	5	5	Nodular
H66	5	5	Nodular
H68[a]	3	3	Laminated
H70	2	2	Laminated
H72	3	3	Nodular
H74[a]	4	4	Nodular
H76	4	5	Nodular
H78[a]	4	4	Nodular
Mean diversity	With ammonites[b] 6.5 ($n=14$)	Without ammonites[b] 3.14 ($n=14$)	
Mean diversity	Nodular facies[b] 12.27 ($n=18$)	Laminated facies[b] 1.3 ($n=10$)	

[a] Beds in which we have recorded ammonites.

[b] Maximum diversity values used.

Fig. 13. Large, oblique ?*Charmasseiceras* in joint surface of Top Tape (bed 29) showing darker fill in body chamber than the host sediment and dog-tooth spar linings to early chambers. Compare with ammonites in Fig. 16A. Note oblique bivalve debris. Chippel Bay, (NGR SY325908). Tape measure 5 cm across.

Fig. 14. Large, vertical ammonite in the base of bed 31, seen on a joint surface. Note the unstably orientated *Gryphaea* above the ammonite. Chisel shaft is 12.5 mm across. Chippel Bay, (NGR SY32989128).

burrows can be used to assess the degree of compaction. In limestones, examples of apparently horizontal burrows with circular cross-sections are common (Fig. 16A,B). This is the case with the trace fossil *Chondrites*, which includes large numbers of individual tubes in each burrow system. Trace fossils in non-limestone units show much more evidence of compaction.

4.3.2. Proportion of cements

The two profiles through beds 19–23 illustrated in Fig. 10 were taken to compare acid insoluble residue (AIR) and carbon and oxygen stable isotope values through the same stratigraphic interval (beds 19–23) with and without a concretion. Seven pairs of samples, one from each profile, occur at the same stratigraphic level (to within 1 cm) and in the same lithology (Table 1). The mean difference in AIR values between these pairs of samples is 1.39% (Fig. 18). Samples 4 and 24 are in the same lithology, but differ in elevation by 1 cm. The mean difference in AIR values between the remaining six pairs of samples is 1.32%. We believe these very slight differences establish the fact that very little difference exists between the AIR values we have derived from the two profiles, other than at the level where the concretion is developed. On this assumption we can use the AIR values for samples between 20 and 30 cm elevation in both profiles to estimate both the amount of diagenetic cement present in the concretion and its stable isotope composition. Assuming the AIR values for the pale marl samples are original, then the difference between the mean AIR values for the pale marl and concretion samples can be used to calculate the proportion of additional carbonate cement present in the concretion. The mean AIR value for concretion samples is about 25% by weight. The proportion of primary biogenic carbonate to diagenetic carbonate in the concretion is given by:

$$\mathrm{AIR(concretion)} + \mathrm{carbonate(marl)} + \mathrm{diagenetic\ cement} = 100\%$$

From Table 2B the two pale marl samples are 49.5% AIR and 50.5% carbonate. In which case AIR(concretion) more or less equals carbonate(marls) and

$$100-(\mathrm{AIR(concretion)} + \mathrm{carbonate(marls)} = \mathrm{carbonate(cement)}$$

$$100-(25+25) = 50.$$

In round figures this gives an average composition of the concretion as 25% AIR, 25% biogenic carbonate and 50% diagenetic carbonate. On the assumption that the concretion is typical of other limestones within the Blue Lias, then these proportions can be used to estimate the isotopic composition of the diagenetic cement. Substituting all values from Table 2A gives approximately 21% AIR, 21% biogenic carbonate and 58% diagenetic carbonate.

4.3.3. Palaeotemperature calculation

Using the modified Craig palaeotemperature equation (Anderson and Arthur, 1983)

$$T^{\circ}C = 16.0-4.14(\delta c-\delta w) + 0.13(\delta c-\delta w)^2$$

where δc=oxygen isotope composition of carbonate and δw=oxygen isotope composition of contemporary Jurassic sea water, oxygen stable isotope values (Table 1) can be converted into palaeotemperatures (Table 5), which summarizes the results for mean δ^{18}O values from the three principal lithologies and the inferred value for limestone cements, assuming a δw value of −1. The results suggest that the cements in the limestone beds were precipitated from pore waters that were about 4 °C lower than the surface waters from which the biogenic carbonate in the pale marls was precipitated. Laminated black shales, on the other hand, contain carbonate that was precipitated from pore waters over three degrees higher than the surface waters. The latter high temperatures are almost certainly due to the presence of small amounts of beef, a deep burial cement for which such elevated temperatures are not unreasonable. Although these arguments are simple and involve a number of assumptions, nevertheless these inferred temperature values are consistent with the idea that the cements in the limestone beds (and concretions) in the Blue Lias were precipitated very early after deposition.

In summary, preservation of ammonites, lack of compaction of trace fossil burrows, and oxygen stable isotope values all suggest early cementation of limestone beds compared with adjacent dark marls or laminated black shales. This early cementation, in turn, may well have resulted from the enhanced porosity in the original pale marl soon after deposition allowing preferential migration of pore waters within these beds, if indeed many were event beds deposited suddenly. Alternatively, it is possible that the event beds were allochthonous and brought in aragonite mud from shallower water, which provided the carbonate for cements. Development of thoroughly cemented horizons probably required substantial time; Allison et al. (in press) suggest that these cemented horizons may reflect intervals of reduced sedimentation (following rapid deposition of the limestone beds). During these intervals cementation took place at shallow depths in a strongly alkaline, stable zone of sulphate reduction. Hardgrounds are unknown in the Blue Lias of Devon and Dorset, so cementation at the sea floor can be eliminated. The conclusion that sedimentation was episodic, rather than a continuous rain of clay-grade particles, seems inescapable.

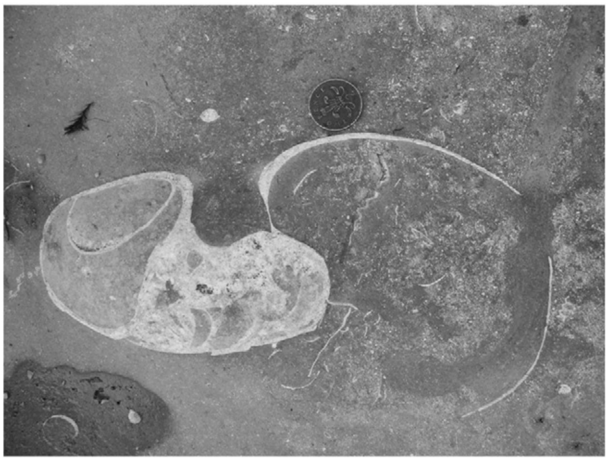

Fig. 15. Large, nearly vertical nautiloid in bedding surface of Third Quick (bed 31). Coin is 25 mm across. Chippel Bay, (NGR SY32899110).

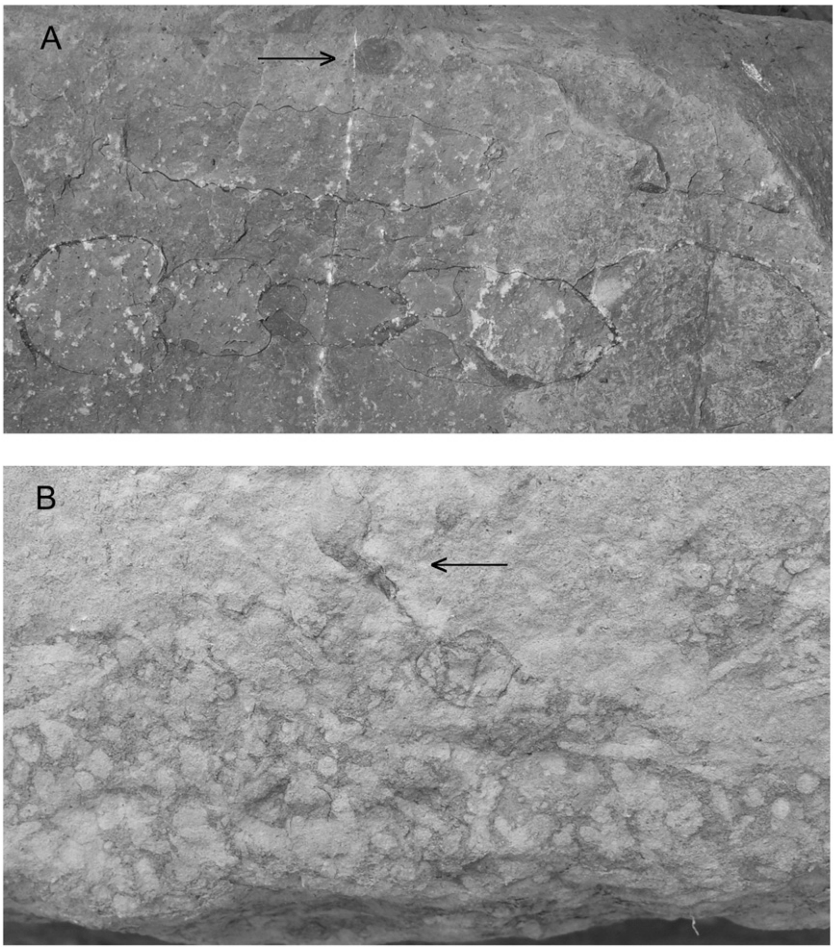

Fig. 16. (A) Nearly circular, dark-filled trace fossil (arrow) in joint surface of Top Tape (bed 29). Note the two ammonites (*Metophioceras*) one above the other with sediment fill identical to the host sediment. Pinhay Bay, (NGR SY32629090). (B) Pale-filled *Chondrites* burrows in base of Second Quick (bed 35) seen on a joint surface. Note frequent circular cross-sections and lack of evidence for compaction. Arrow indicates an oblique ammonite with crushed inner whorls and *Chondrites* reworking the sediment fill of the body chamber. Chippel Bay, (NGR SY32949118).

4.4. Summary: controls on ammonite occurrence

Returning to the issue raised in the Introduction, we argue that the occurrence of ammonites in a particular bed is a function of palaeoecology, taphonomy and diagenesis. Evidently, many ammonites were not really independent of benthic conditions. They were probably nektobenthic and needed oxygenated bottom waters to survive. Thus they are not preserved in beds that reflect highly dysoxic or anoxic conditions. Shells of open-water ammonites might be expected to have sunk to the sea floor and been preserved independent of lithofacies. However, the aragonitic shells would have been susceptible to dissolution on the seafloor unless rapidly buried in alkaline sediments. So it is possible their absence in laminated black shales is due to dissolution before burial rather than palaeoecology. We do not think this is the case because ammonites are also rare in laminated limestones, especially in the Hettangian part of the section where our survey found very few. Most ammonite beds show some evidence for pulses of rapid sedimentation. Ammonites are best preserved and most identifiable in beds that experienced early diagenetic cementation. Hence, a combination of oxygenated bottom waters, pulses of rapid sedimentation and subsequent stable intervals without sedimentation may have been the key to preservation of the best ammonite beds: the nodular and planar-bedded limestone facies.

Fig. 17. Very large, pyritized ammonite on the basal surface of a loose block from Grey Ledge (bed 49). Pinhay Bay, (NGR SY32659090).

4.5. Blue Lias rhythms

The origin of the rhythms has been controversial and indeed still is. See, for example, the conflicting opinions of Hallam (1957, 1960, 1964, 1986), Campos and Hallam (1979), Hart (1982), House (1986), Weedon (1986, 1987), Bottrell and Raiswell (1990), Moghadam and Paul (2000) and Sheppard et al. (2006). Much of the controversy has arisen

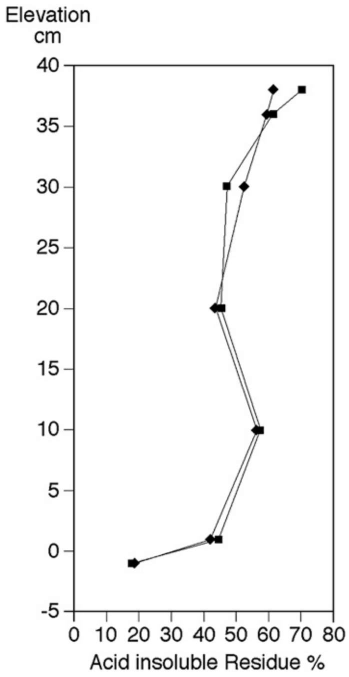

Fig. 18. Comparison of acid insoluble residue values at comparable levels and in the same facies in the two profiles shown in Fig. 10. Note that the values are almost identical.

because two related, but distinct, questions have not been distinguished. The first concerns the origin of the rhythmic sedimentation; the second concerns the origin of the limestone beds. Differences between trace fossil fill and host sediment (Hallam, 1957; Hart, 1982; Moghadam and Paul, 2000; Martin, 2004) clearly show that there were original differences in sediment when the burrows were being filled. Pale-filled burrows in darker host sediment (Fig. 16B) and vice versa (Figs. 16A and 19) are equally common and in many cases one can trace the overlying sediment down into the burrows. The rhythmic alternations of lithologies are primary. Depositional models which assume the Blue Lias was initially homogeneous sediment, which subsequently 'unmixed diagenetically' are just not tenable. Furthermore, since not all rhythms contain limestone beds (Fig. 4), analysis of alternations of limestone versus 'non-limestone' beds is unlikely to detect any possible causal mechanism.

Nevertheless, the limestones have clearly been diagenetically altered by addition of calcium carbonate cement. The best field evidence for this is that some limestone bands change laterally from continuous limestone with occasional uncemented patches to continuous marl with occasional concretions. Lower Mongrel (bed 21) does this in a distance of about 30 m in Chippel Bay (NGR SY33009124). Mean insoluble residue values (Table 2) indicate that limestones contain about 28% more carbonate than pale marls; 23% more at the level of the concretion. This extra carbonate is assumed to be cement. However, mean $\delta^{18}O$ values for all limestone and marl samples differ by only 1‰ and 0.6‰ for the concretion level (Table 2), suggesting that the carbonate cement had a similar isotopic composition to the primary biogenic carbonate. By implication, the pore waters from which the cement was precipitated were similar to the seawater from which the biogenic calcite was precipitated and therefore cementation of the beds was very early in the diagenetic cycle. Laminated black shales show the most modified $\delta^{18}O$ values (and highest inferred palaeotemperatures) and we suggest that this is due to the presence of fine beef (fibrous calcite) layers in them. Macroscopic beef layers can be detected in laminated black shales at about the level of the isotope samples in the Blue Lias.

Table 5
Inferred mean palaeotemperatures for the three principal lithologies in the Blue Lias Formation, Chippel Bay, Lyme Regis and for cements in the limestone beds

Lithology	Mean $\delta^{18}O$	Palaeotemperature °C	Range °C
Laminated black shale	−5.181	35.6	31.6–38.7
Pale marl	−4.555	32.4	30.0–37.9
Limestone	−3.774	28.5	23.7–33.4
Cement	−3.384	26.6	No value

Blue Lias rhythms involve two cycles, redox and carbonate. Alternations of laminated sediments lacking trace fossils with bioturbated sediments demonstrate the redox cycles (Moghadam and Paul, 2000; Martin, 2004). Alternations of dark, siliciclastic-rich sediments (up to 90% AIR) with pale marls or limestones (with 5–50% AIR) indicate the carbonate cycles. In parts of the formation these cycles are in phase at the scale of individual rhythms, giving rise to the sedimentary successions illustrated in Fig. 4. However, locally in the section all sediments are laminated (e.g. beds H32–H36) indicating that the redox cycles ceased, while the carbonate cycles continued. Equally, high in the succession (above bed 31, Third Quick) limestone beds are widely separated, indicating that the carbonate rhythms became out of phase with the redox rhythms. Rhythmic bedding ceased in the overlying Shales-with-Beef Member of the Charmouth Mudstone Formation.

An unusual feature of the Blue Lias rhythms is the bundling of beds of nodular facies and laminated limestone facies. Bundling in rhythmic successions commonly results from harmonics between the circa 20 thousand year (ky) precession cycle and the circa 100 ky eccentricity cycle (e.g., Gale, 1990; House, 1995). In which case ideally bundles of five rhythms should result. Furthermore, the effect of the precession cycle is minimal when the eccentricity of the Earth's orbit is minimal and vice versa. Hence bundled rhythmic successions usually have cyclic

Fig. 19. Dark-filled *Arenicolites* burrow in joint surface of Under White (bed 9). West side of Pinhay Bay, (NGR SY31589050).

variations in thickness of beds or carbonate content. House (1986, Fig. 1; 1995, Fig. 11) illustrates a spectacular example from the Jurassic of Morocco. The horizons low in the Blue Lias that Lang (1924) identified as forming conspicuous reefs on the foreshore in Pinhay Bay (H30, H42, H54, H66, H72, Figs. 4 and 6) almost certainly fall into this category. What is unusual, and was first noted by Hallam (1960), is grouping into a bundle of one facies (e.g., nodular limestone facies) followed by a bundle of another (laminated limestone) facies. Since the nodular limestone facies is richly fossiliferous and the laminated limestone facies is nearly barren, this implies that for about 100 ky the sea floor was periodically suitable for life, followed by about 100 ky when it was unsuitable. We suspect this may reflect sea-level fluctuations superimposed on orbital forcing mechanisms, but are uncertain of the details. This is an aspect of Blue Lias sedimentation that requires further investigation. Hallam (1960) reported that the same bundles could be traced, bed for bed, in the Blue Lias of South Wales. Thus we do not think the bundling is a local phenomenon.

5. Conclusions

(1) The Blue Lias Formation is a rhythmic sedimentary unit with three principal lithofacies, laminated black shales, dark grey marl, and pale marl. This last is often cemented into hard limestone bands. Limestones can be further differentiated into nodular, planar-bedded and laminated limestone facies.

(2) Ammonites are so far unknown in over two thirds of the individual beds of the Blue Lias and significant gaps without ammonites occur presenting difficulties in recognizing zonal and subzonal boundaries.

(3) Ammonites are predominantly present in bioturbated nodular and planar-bedded limestone facies.

(4) Co-occurrence with obvious macrobenthos and absence from beds lacking benthos suggest that Blue Lias ammonites were nektobenthonic.

(5) Ammonites preserved in ‘non-limestone’ units and laminated limestones are typically crushed, those in nodular and planar-bedded facies limestones are preserved in three dimensions and are often spar-filled.

(6) Ammonites (and other tabular fossils) are commonly randomly orientated with respect to bedding, suggesting rapid deposition in event beds.

(7) Presence of erosional scours and exotic sediment filling ammonite chambers and trace fossil burrows implies erosion by traction currents. Absence of encrusting oysters on large cephalopod (and other large) shells implies rapid burial in event beds. Blue Lias sedimentation was episodic rather than a continuous settling from suspension in a quiet environment.

(8) Stable isotopes of carbon and oxygen are most negative in laminated black shales and least negative in limestones, showing a clear diagenetic trend, which correlates very well with acid insoluble residue values.

(9) Stable isotope values imply early cementation of limestone beds from pore waters similar in composition to contemporary Jurassic seawater.

(10) Preservation of ammonites resulted from suitable original palaeoecological conditions, rapid deposition and early diagenetic cementation of limestones.

(11) Differences between trace fossil fill and host sediment clearly demonstrate that Blue Lias rhythms are primary, but limestone beds are equally clearly diagenetically altered by the addition of carbonate cement.

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