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Sedimentology of the Triassic–Jurassic boundary beds in Pinhay Bay (Devon, SW England)

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WIGNALL, P. B. 2001. Sedimentology of the Triassic–Jurassic boundary beds in Pinhay Bay (Devon, SW England). *Proceedings of the Geologists' Association*, **112**. 349–360. New exposures in Pinhay Bay (SE Devon) of the White Lias (Langport Member of the Lilstock Formation) and basal Blue Lias reveal rapidly changing palaeoenvironments during the Triassic–Jurassic (T–J) boundary interval. During deposition of the topmost White Lias a soft seafloor of micritic mudstone was lithified and bored. The resultant hardground was locally eroded, probably in a shallow marine setting, to form a spectacular intraformational conglomerate that was itself lithified. Brief subaerial emergence then followed and produced a fissured and pitted top surface to the White Lias. The regression was short lived and rapid transgression at the base of the Blue Lias established organic-rich shale deposition with a small framboidal pyrite population and low Th/U ratios indicative of a stable, sulphidic lower water column (euxinic conditions). The White Lias/Blue Lias contact thus records a short duration, high amplitude relative sea-level change. This sea-level oscillation has also been postulated for other T–J boundary sections in Europe, although the failure to identify it in regional-scale sequence stratigraphic studies is probably due to its brief duration. Deposition of the basal beds of the Blue Lias was marked by a discrete phase of syn-sedimentary folding and small growth fault activity that may record a regional pulse of extensional tectonic activity.

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1. INTRODUCTION

The Triassic–Jurassic (T–J) boundary interval coincides with both a mass extinction crisis and major sea-level oscillations (Hallam & Wignall, 1999). Crucial evidence for the latter comes from Pinhay Bay on the SE coast of Devon, where truncated burrows of *Diplocraterion* suggest a relative sea-level fall (Hallam, 1960a, 1988, 1997, 2001). However, in contrast, Hesselbo & Jenkyns (1998, fig. 4) recognized no major sea-level change at this level in Pinhay Bay. Resolution of these contrasting views has been hindered by the limited amount of section accessible at Pinhay Bay, but recent coastal erosion has revealed new outcrops of the contentious interval. These are recorded here.

Stratigraphy

Latest Triassic deposition in SW England is recorded by the Penarth Group, which consists of the Westbury Formation, an organic-rich shale unit, and the Lilstock Formation. This unit is in turn divided into the Cotham Member, a calcareous, green-grey shale, and the Langport Member, formerly known as the 'White Lias', a clean micritic mudstone that reaches 8 m thick on the south Devon coast (Fig. 1). The top bed of the White Lias is known as the 'Sun Bed' due to the reported presence of desiccation cracks on its top surface (Richardson, 1906, 1911; Hallam, 1960a; Donovan & Kellaway, 1984). On the south coast of Devon the base of the overlying Blue Lias Formation is marked by a sharp contact between a laminated, organic-rich shale, called the 'Paper Shale' by Richardson (1911), and the Sun Bed. However, in Somerset a thin shale unit, known as the Watchet Member (*sensu* Hallam, 1990), occurs between the White Lias and the Paper Shale. The Watchet Member may be a contemporaneous, but more distal, facies than the White Lias (Poole, 1979) in which case its

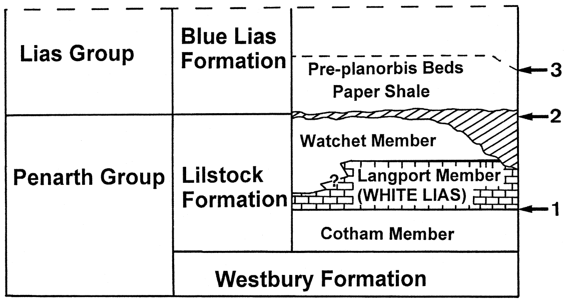

Fig. 1. Summary of the lithostratigraphy of the Triassic–Jurassic boundary succession of SW England. Cross-hatching between the Penarth and Lias groups depicts postulated erosion. The various proposed levels for the Triassic–Jurassic boundary are numbered: (1) from Poole (1979); (2) from Richardson (1911), George *et al.* (1969) and Hallam (1990); and (3) from Cope *et al.* (1980) and Warrington *et al.* (1994).

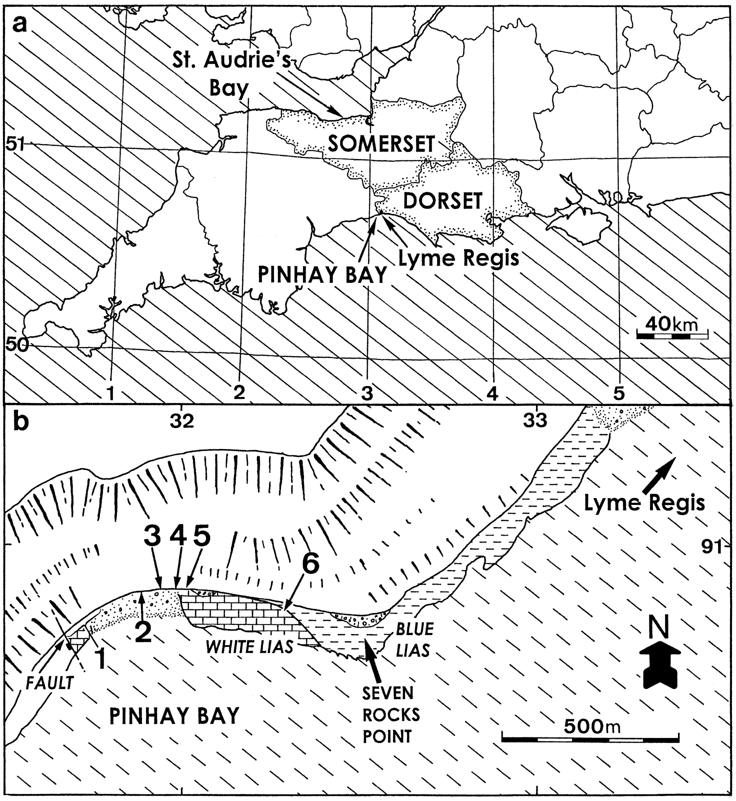

Fig. 2. Location of (**a**) Triassic–Jurassic boundary sections in SW England; (**b**) sections 1–6 in Pinhay Bay, SE Devon.

absence from south Devon could be due to lateral facies change. Alternatively, the Watchet Member may have been removed by erosion in this area, prior to Blue Lias deposition (Hallam, 1981, 1990; Hart, 1982), with obvious greater significance for inferred sea-level changes.

The Blue Lias consists of small-scale alternations of organic-rich shales, marly mudstones and bioclastic limestones (Hallam, 1960b). The first Jurassic ammonite *Psiloceras planorbis* (J. de C. Sowerby) appears some distance above the base of the Blue Lias (Hodges, 1994), with the result that basal beds of this unit are known as the Pre-planorbis Beds, or sometimes the Ostrea Beds due to the abundance of the oyster *Liostrea hisingeri* (Nilsson) at this level (Lang, 1924). Lateral thickness variations of the Pre-planorbis Beds are probably partly due to the diachronous appearance of *P. planorbis* (Hodges, 1994). At Pinhay Bay they are 2.7 m thick (Lang, 1924).

The placement of the Triassic–Jurassic boundary has been controversial. Several workers have suggested that the base of the Jurassic be taken at the lowest appearance of *P. planorbis* (Torrens & Getty, 1980), in a proposed global stratotype section at St. Audrie's Bay in Somerset (Warrington *et al.*, 1994; Fig. 2). Other workers have preferred the base of the Blue Lias as the system boundary (Richardson, 1911; George *et al.*, 1969; Hallam, 1990), or the base of the Langport Member (Poole, 1979).

Pinhay Bay sections

Pinhay Bay is a broad coastal embayment lying 2.5 km west of Lyme Regis (Fig. 2). At the west end of the bay the White Lias is exposed in the footwall of a normal fault (section 1 in Fig. 2). This section has been much photographed (e.g. Woodward, 1906, pl. vi; Hallam, 1960a, pl. 5; Swift, 1999, pl. 4, figs 1 & 2) and discussed, since De La Beche's address to the Geological Society in 1848 (cf. Richardson, 1906, p. 407), although only Hallam (1960a) has provided a detailed study of the sediments. Due to the regional dip, the White Lias descends to beach level in the centre of the bay and passes onto the foreshore at the eastern end of the bay (Fig. 2). However, for over 100 years the boundary with the Blue Lias has been mostly obscured by debris from coastal landslips and beach material, with the result that it could only be examined high in the cliff face or on the foreshore. Thus, in his report of a Geologists' Association field excursion, Woodward (1889, p. xxx) noted that the top of the White Lias in the centre of Pinhay Bay was 'covered by a thick mass of Blue Lias limestones'. The contact was still inaccessible to the Geologists' Association over 90 years later (Sellwood *et al.*, 1970) and, as recently as 1999, it was noted that the top of the White Lias was poorly exposed in Pinhay Bay due to beach build-up and landslips (Swift, 1999). However, a visit to Pinhay Bay in June 2000 revealed that recent coastal erosion had removed much of the landslip material from the centre of the bay with the result that several new sections, including a splendid, 20 m wide cliff, were visible (and accessible). These have revealed a previously unknown diversity of sedimentary features around the White Lias/Blue Lias contact which are documented here.

2. STUDY TECHNIQUES

Detailed logs were made of the uppermost beds of the White Lias and basal beds of the Blue Lias at sections numbered 2 to 6 within Pinhay Bay (Fig. 2). Sections 2 to 5 consist of a discontinuous series of cliff exposures, whereas section 6 is seen on the foreshore immediately to the west of Seven Rocks Point. Lang's (1924) bed numbering scheme for the Blue Lias is readily applicable and is utilized here. Hallam (1960a) provided bed numbers for the White Lias in section 1, but such is the rapid lateral variation that they are difficult to apply in the other sections. Blocks were collected for polishing in order to examine the smaller-scale sedimentary and biogenic structures. An unweathered block from the centre of the Paper Shale, collected from section 6, was cut and polished and examined using the backscatter facility of a scanning electron microscope (SEM). This enabled the size distribution of the abundant pyrite framboids in this lithology to be measured.

A field portable gamma-ray spectrometer was used to measure the concentrations of the gamma-ray-emitting elements K, U and Th at section 6. This location has the advantage of being essentially unweathered, and it also provides extensive bedding plane exposures, thus maximizing the vertical resolution to around 20 cm (cf. Myers & Wignall, 1987). Note that measurement on vertical faces would provide average concentrations from roughly 1 m of vertical section, and so would be unable to resolve the sub-metre scale vertical variations of lithology within the Blue Lias.

3. SEDIMENTOLOGY

The vertical succession of facies is discussed section by section (cf. Fig. 2).

Section 1

This section was documented in detail in Hallam (1960a), was also recorded in Hesselbo & Jenkyns's (1995) log and is only discussed briefly here. The uppermost 6 m of the White Lias are currently exposed (as of August 2000) at this location and reveal a diversity of sedimentary features. A metre-thick, matrix-supported, intraformational conglomerate, with rounded, centimetre-sized clasts, occurs near the base. This is Hallam's (1960a) bed 4, which Hesselbo & Jenkyns (1995) interpreted to be a product of redeposition. Further evidence of seafloor instability is also present higher in the section where slumping is well developed (Hallam's bed 8). Hallam (1960a) also described 'wedge bedding' in horizons displaying substantial lateral thickness variations. This feature is well displayed in bed 3 where the thickness variations reflect the strongly erosive basal contact (see description of the similar "scour-and-drape" bed in section 2).

Section 2

The lowest exposed bed of the White Lias in section 2 consists of intensely stylolitized micritic limestone with a somewhat rubbly weathering appearance (Fig. 3). The overlying micritic mudstone is the porcellaneous variety of Hallam (1960a) and has a distinctive splintery fracture. It rests on a markedly erosive contact that is seen to cut down up to 0.5 m at the eastern end of section 2 (section 2b in Fig. 3). Laminations within the porcellaneous limestone parallel the basal erosive contact and thus record purely aggradational infill of the erosive topography. This horizon is therefore informally called the 'scour-and-drape' bed. The topmost few centimetres of this bed contain a bivalve fauna that includes *Modiolus hillanus* (J. Sowerby) and *Gervillella* sp. The overlying beds in section 2 consist of alternations of massive, decimetre-thick beds of micritic mudstone and thinner, marly micrites. The topmost micritic limestone bed displays erosive-based sets of laminae defining erosive-based troughs (typically 10 cm wide and 1 cm high) that somewhat resemble the internal lamination of oscillatory ripples. Ripple structures have been reported from elsewhere in the topmost beds of the White Lias (Donovan & Kellaway, 1984; Swift, 1995). However, such bedforms could not develop in such fine-grained micritic sediment. Instead, the laminations must be the product of erosion of a micritic substrate followed by settling of the suspended micrite – a small-scale version of the events recorded by the scour-and-drape bed.

The topmost bed of the White Lias consists of a spectacular intraformational conglomerate resting on a strongly erosive basal surface (Fig. 4). Clasts range from 25 cm in diameter to a few millimetres with the larger clasts being distinctly more angular and tabular than the smaller, more rounded examples. The larger clasts tend to occur in areas with a high clast density where the conglomerate is clast supported, but at most levels the clasts are supported by the micrite matrix and randomly orientated (Fig. 5a). Many of the largest clasts have clearly been derived from beds of the trough-laminated micrite (which has been removed by erosion at the western and eastern end of the section). The thin marly interbeds appear to have been unlithified and microconglomerate has penetrated along these layers, in some instances totally undercutting the micritic beds whilst leaving them *in situ*. Other large

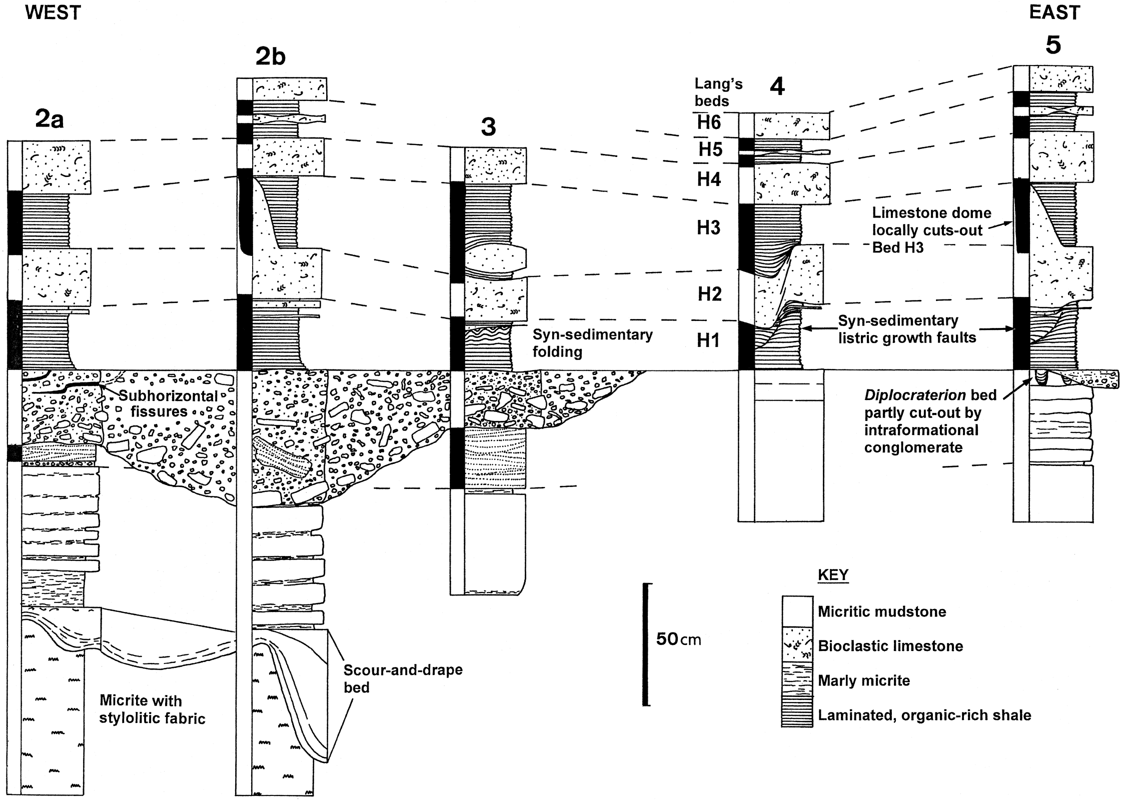

Fig. 3. Log correlation panel of top White Lias/basal Blue Lias sections within Pinhay Bay. The left-hand column of the graphic log depicts the presence of fine lamination (in black).

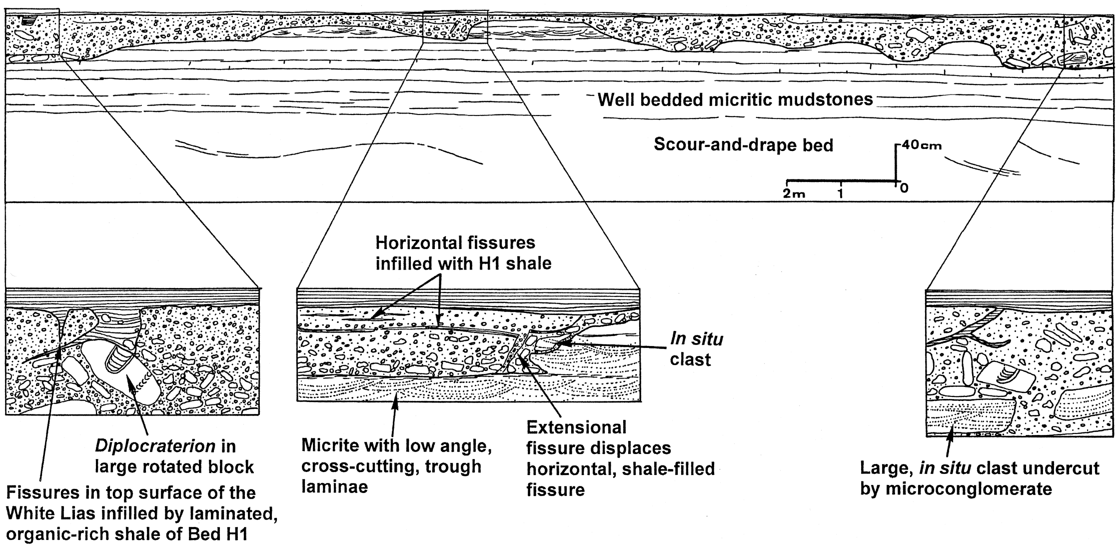

Fig. 4. Field sketch of the intraformational conglomerate at the top of the White Lias in section 2, Pinhay Bay with three sketches showing, in detail, the range of sedimentary features seen within the conglomerate.

Fig. 5. (**a**) Intraformational conglomerate at the top of the White Lias in section 2, showing poor sorting and random clast orientation. Lens cap is 5 cm in diameter. (**b**) Sharp contact between the White Lias conglomerate and the Blue Lias Paper Shale (Bed H1) in the centre of section 2. Laminated shale infills a horizontal fissure in the White Lias 4 cm beneath the tape measure. Tape measure is 67 mm wide. (**c**) Micrite-filled dyke (arrowed) penetrating into the base of the Paper Shale at the western end of section 2. (**d**) Section 4, showing a monoclinal flexure in the limestone of Bed H2 behind, and to the right of, Thomas Wignall, aged 7.

clasts contain *Diplocraterion* burrows and come from a bed that is not seen *in situ* in this section. Finely laminated shales (the Paper Shale (Bed H1) of the Blue Lias) drape the slightly uneven top surface of the intraformational conglomerate and have penetrated into cracks and sub-horizontal fissures in the conglomerate (Fig. 5b). In a few cases the shale-filled fissures have been cut by high angle, centimetre-wide extensional fissures infilled with microconglomerate. A single example of a micrite-filled dyke penetrates up into the lower half of the Paper Shale at the western end of section 2 (Fig. 5c).

Bed H1 (the Paper Shale) is an organic-rich shale with well-developed silt laminae, up to 3 mm thick, in its lower and upper third. Fossils are absent with the exception of a single bedding plane in the centre of the bed, covered in disarticulated valves of *Modiolus minimus* (J. Sowerby) and echinoid spines. Towards the top of H1 centimetre-thick levels have been calcite cemented with the result that the transition to the overlying limestone (Bed H2) is essentially gradational. The base of Bed H2 is finely laminated, but most of the bed is thoroughly bioturbated and has a shelly fauna dominated by*Liostrea*. The top of H2 is also finely laminated and this style of bedding continues into the overlying organic-rich shale of Bed H3. In section 2b, Bed H3 is locally cut-out by the development of a dome of limestone from the top of Bed H2, a feature also seen in section 5. Bed H4 is another limestone and, like H2, it is laminated at its base and top and bioturbated in the centre (Fig. 3). Bed H5 is another, finely laminated, organic-rich shale, in this case with a thin parting of bioclastic limestone.

Section 3

Roughly 30 m to the east of the eastern end of section 2, a small section reveals a similar succession of facies (Fig. 3). Alternations of micritic mudstone and thin interbeds of marly micrite occur in the upper White Lias, and are sharply overlain by an intraformational, clast-supported conglomerate. The largest clasts occur in the middle of the bed and many are bored (Fig. 6a). The Paper Shale rests sharply on the top surface of the conglomerate and displays small-scale folds that have been partly truncated by syn-sedimentary erosion (Fig. 7). The overlying Blue Lias stratigraphy is similar to that seen in

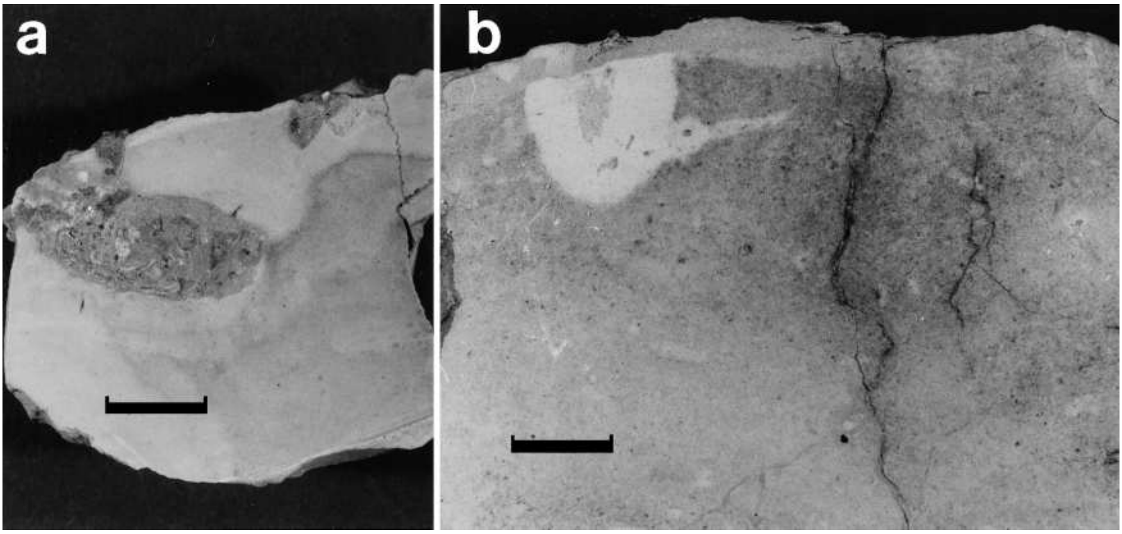

Fig. 6. White Lias polished blocks: (**a**) clast from the intraformational conglomerate at section 3, showing borings penetrating the surface. Infill consists of oyster valves and gypsum crystals (probably a weathering product derived from pyrite oxidation); (**b**) truncated U burrow from the topmost White Lias, section 5, with a thin veneer of marl with oyster valves on the erosion surface. 1 cm scale bars.

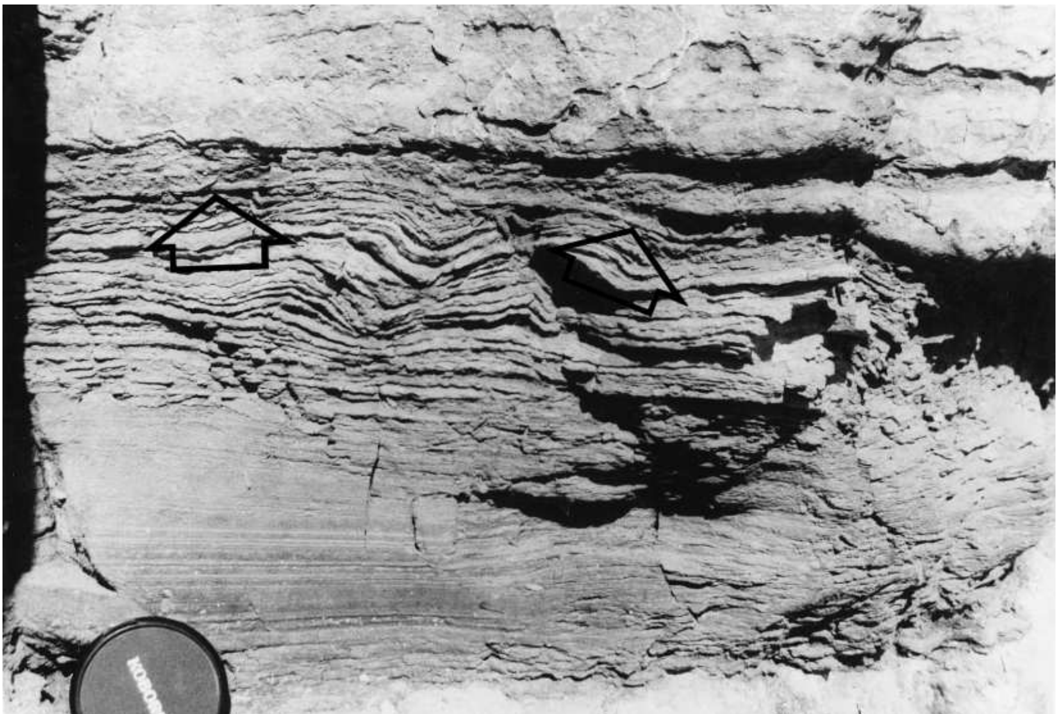

Fig. 7. Paper Shale (Bed H1) at section 3 displaying syn-sedimentary folding. At the level marked by arrows erosion has partly removed the folded beds and a lens of limestone, seen in the right of the photograph, partially infills the scoured hollow. Lens cap is 7 cm diameter.

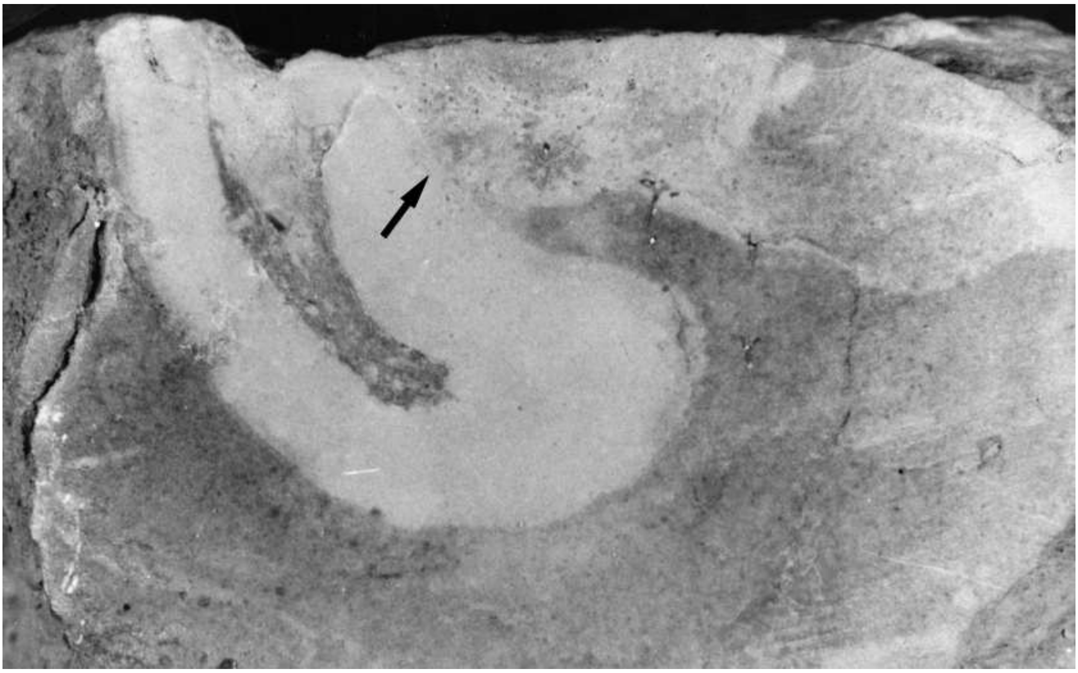

Fig. 8. Polished block showing the uneven top surface of the White Lias at section 5, and a faintly visible *Diplocraterion*. Erosion has removed all but the base of the burrow and it has been cross-cut by a later U-burrow infilled with clean micrite. An arrow indicates the point of cross-cutting. Field of view is 5 cm wide.

section 2 but with a thin rib of limestone developed in the lower half of Bed H3 (Fig. 3).

Section 4

A short distance to the east of section 3 (Fig. 2), a further small exposure reveals the topmost beds of the White Lias. No intraformational conglomerate is found at this location, instead the topmost beds consist of weakly bedded micritic mudstones. The most noteworthy feature in the overlying Blue Lias consists of a monoclinal flexure in Bed H2 (Fig. 5d), which passes laterally into an extensional fault (with 30 cm displacement), that downthrows to the west. Substantial thickness variations in the overlying shale (Bed H3) ensure that Bed H4 is undisturbed by this folding/faulting, and indicate its syn-sedimentary origin.

Section 5

The topmost beds of the White Lias are once again exposed in section 5 where, at the eastern end of the outcrop, common *Diplocraterion* are seen to penetrate the top surface. Many of these burrows have been truncated with the result that only the basal part of the 'U' is preserved (Fig. 6b). The burrows are also frequently cross-cut by other burrows, including flask-shaped and U-shaped examples (Fig. 8). These have well-defined margins, suggesting they penetrated a stiff substrate, and are infilled with pale cream micrite that contrasts with the light grey micrite of the remainder of the bed. Rare oysters are found encrusting the top surface of the White Lias. At the western end of the section an erosion surface cuts down through the *Diplocraterion* bed to progressively deeper levels within the White Lias. The surface is overlain by a grey, marly clay with common oyster valves (Fig. 6b). In its thickest development at the west end of the section the clay contains intraclasts of White Lias pebbles. This is thus another development of intraformational conglomerate, although with a matrix that is distinctly more marly than the pure micrite matrix seen in sections 2 and 3. The overlying basal beds of the Blue Lias have once again been affected by several syn-sedimentary growth faults with a downthrow direction consistently to the west.

Section 6

The easternmost section of the White Lias, seen on the foreshore, lacks the intraformational conglomerate and is instead capped by a massive, pale grey, micritic limestone. Hallam (1960a, b, 1988) reported desiccation cracks and truncated *Diplocraterion* from the top of the White Lias on the foreshore, but no examples were seen during this study. Syn-sedimentary deformation features are absent from the basal Blue Lias beds in this section.

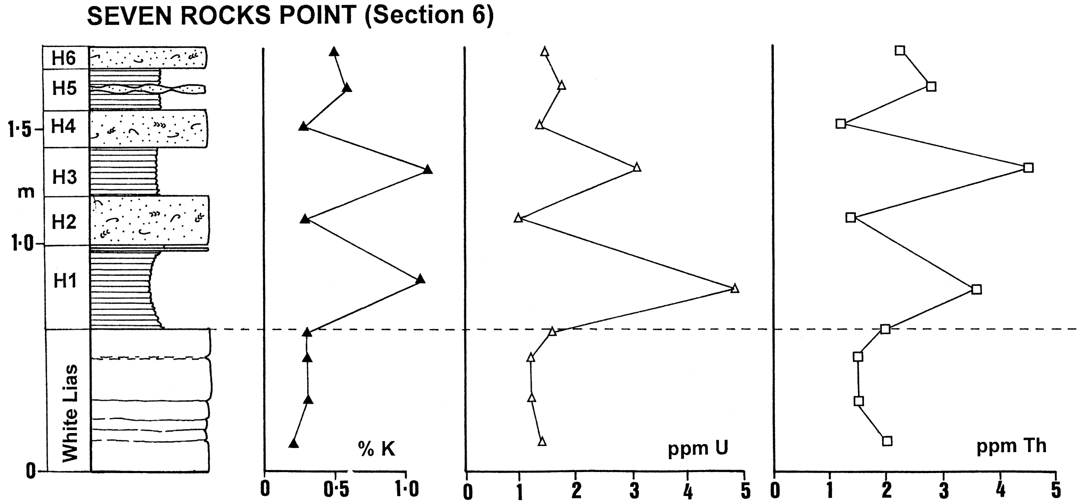

Fig. 9. Fluctuations of K, U and Th, measured by field portable gamma-ray spectrometer at section 6. Key as for Figure 3.

4. SPECTROMETRY AND PYRITE PETROGRAPHY

Spectral gamma ray analysis of section 6 revealed uniformly low concentrations of K, U and Th in the White Lias (Fig. 9). In contrast, the Blue Lias shows substantial oscillations that coincide with the lithological changes, the shales being distinctly more enriched in all radionuclides. The magnitude of the U oscillations declines markedly from Bed H1 upwards, thus the Th/U ratios for the three shales assayed, H1, H3 and H5, increases from 0.8 to 1.5 to 1.6 respectively.

Backscatter SEM examination of the Paper Shale revealed an abundant pyrite content with both crystalline and framboidal varieties (Fig. 10). Measurement of framboid diameters revealed a population dominated by small examples (mean diameter 4.5 μm) with little variation (Fig. 11). Only one framboid out of 175 measured had a diameter larger than 10 μm.

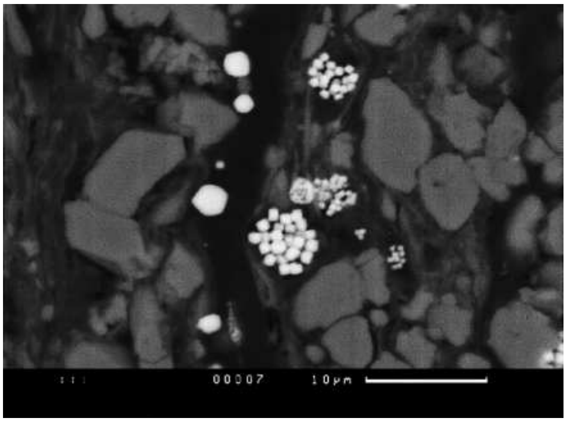

Fig. 10. Backscatter SEM image of a polished surface of the Paper Shale (Bed H1) from section 6. Pyrite appears as white grains and occurs as aggregates of microcrysts (framboids) and as polyhedral crystals which are concentrated within, and at the border of, a layer of black organic matter. Angular grains of quartz (<10 μm in diameter) occupy much of the field of view. Note that bedding runs vertically in this image.

5. ENVIRONMENTAL CHANGE AT THE T–J TRANSITION

Previous studies of the White Lias have noted the restricted range of marine taxa and occasional presence of evaporite minerals (celestine) and postulated a variable salinity regime in a somewhat restricted marine environment (Hallam, 1981; Hallam & El-Shaaraway, 1982; Swift, 1995). The uniformly fine-grained carbonate further indicates tranquil depositional conditions, albeit occasionally interrupted by seismic events, responsible for the slump horizon, and storms. Major phases of erosion recorded by the 'scour-and-drape' beds, and the smaller-scale erosive events responsible for the trough-laminated micritic beds, probably record this storm activity. The White Lias has a considerable regional extent (cf. Donovan *et al.*, 1979) and may pass distally into shalier facies of the Watchet Member (Poole, 1979; Swift, 1999). Both its extent and lack of beach-barrier facies suggest that a lagoonal epithet is inappropriate for the White Lias. Instead, deposition probably occurred in a broad shallow seaway of slightly abnormal salinity with dampened tidal activity and perhaps limited wave fetch.

The final events in the deposition of the White Lias at Pinhay Bay can be resolved into a series of discrete phases (Fig. 12). In phase 1 *Diplocraterion* burrows penetrated down up to 20 cm into the topmost surface of the White Lias (cf. Hallam, 1988), before erosion removed the upper part of the burrows (phase 2). The

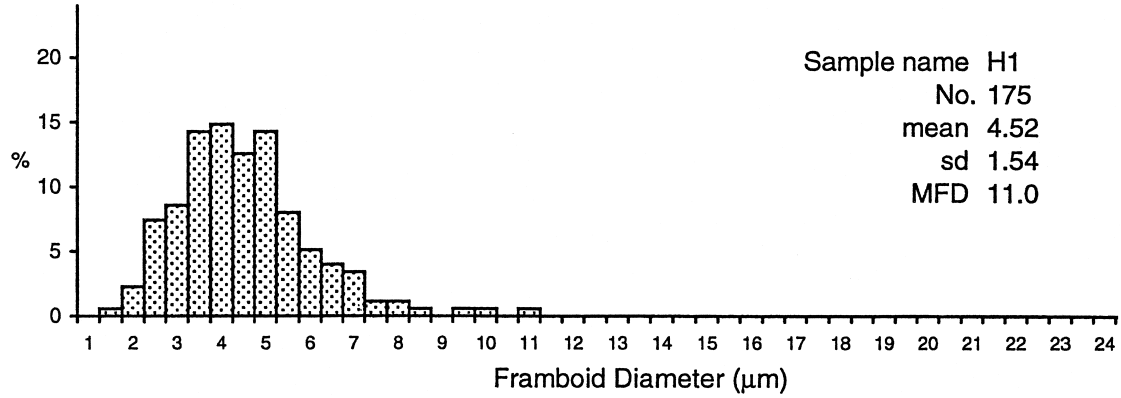

Fig. 11. Size distribution of framboid diameters in a sample of the Paper Shale (H1). sd, standard deviation; MFD, maximum framboid diameter.

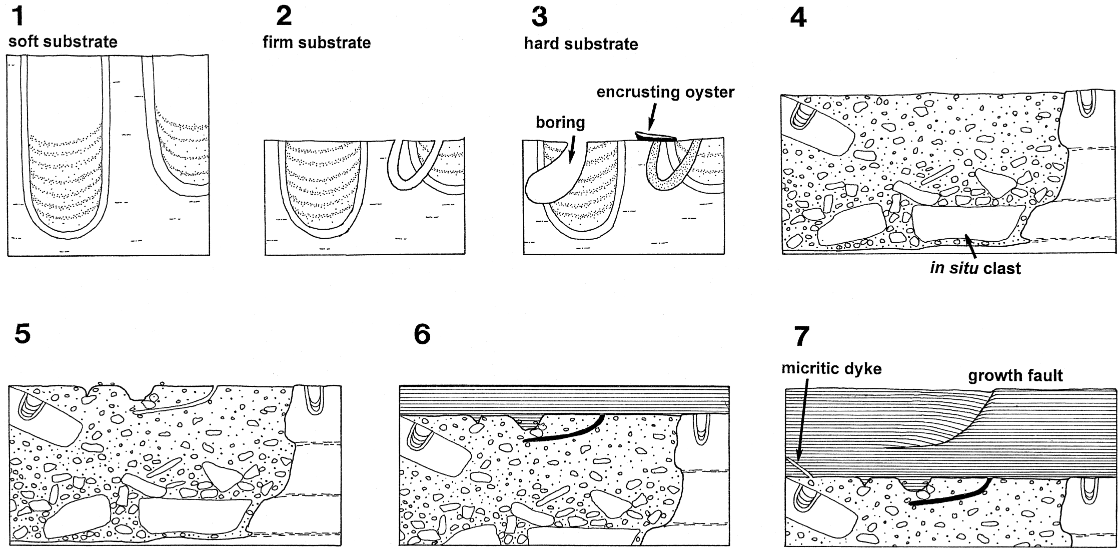

Fig. 12. Phases in the formation of the White Lias/Blue Lias contact at Pinhay Bay. (1) Development of *Diplocraterion*-burrowed micrite in soft sediment. (2) Partial erosion of *Diplocraterion* and development of a firm ground. (3) Lithification of seafloor and boring and encrustation of resultant hardground. (4) Erosion and redeposition of upper White Lias. (5) Lithification of intraformational conglomerate and development of cracks and fissures, probably during subaerial exposure. (6) Rapid transgression and infill of dissolutional topography by laminated, organic-rich, silty shale (the Paper Shale). (7) Growth faulting during later stages of Paper Shale deposition.

erosion appears to have exposed a semi-lithified substrate on the seafloor and the truncated *Diplocraterion* are cross-cut by burrows with sharp margins. Seafloor lithification was completed in phase 3 and both the *Diplocraterion* and firm-ground burrows are cross-cut by borings. Oysters are also occasionally found cemented to the top surface.

Phase 4 saw the local erosion and redeposition of the topmost beds of the White Lias (Fig. 12). The *Diplocraterion* and trough-laminated horizons were clearly lithified prior to this phase and provide many of the larger clasts within the intraformational conglomerate. However, other horizons were unlithified and probably provided the micrite matrix which is locally seen to undercut blocks, most notably by penetrating along thin, marlier layers. It is unclear if phase 4 records a submarine or subaerial erosive event, although the rare presence of oysters within the matrix suggests they were present on the seafloor immediately prior to erosion, a hint that the event was submarine. Hesselbo & Jenkyns (1995) suggested that the celestine ($SrSO_4$) reported by I. M. West in Hallam & El Shaarawy (1982), from the White Lias, may be a replacement of gypsum. Thus, potentially, evaporite dissolution may have contributed to the break up of the beds. However, the high Sr levels could equally record diagenetic enrichment, because the underlying Mercia Mudstones contain economic-grade celestite (Duff, 1992), which may have sourced Sr-rich groundwaters. The presence of a lithified bed above unlithified strata may have led to overpressuring which could have further contributed to the disruption of the uppermost White Lias. The internal details of the intraformational conglomerate unfortunately offer few clues to its ultimate origin. Its poor grading, often chaotic clast organization and lateral variability suggest a high concentration sediment gravity flow that probably 'froze' after only a short distance of movement.

The intraformational conglomerate was lithified during phase 5 and fissures and hollows were locally developed on the upper surface. More commonly, a series of horizontal fissures were developed roughly 10 cm beneath the top surface. These may have formed by dissolutional enlargement of listric faults. This dissolutional phase in the development of the top of the White Lias provides the best evidence for subaerial exposure, although the lack of a well developed karstic surface suggests only brief emergence.

The transition from phase 5 to 6 records the greatest environmental change within the boundary interval. Conditions of subaerial emergence were replaced by the anoxic, marine deposition of the Paper Shale which drapes the somewhat irregular top surface of the White Lias and infills the fissures and hollows. The predominance of tiny framboids within the pyrite fraction of the shale (Fig. 11) is typical of modern euxinic environments, where framboids form at the top of a sulphidic lower water column (Wilkin *et al.*, 1996). Because such dense particles sink rapidly, only a short time is available for framboid growth and they consequently rarely exceed 6 μm in diameter. The Th/U ratio of the Paper Shale is very low, even by black shale standards (cf. Myers & Wignall, 1987), and is further evidence for the prolonged euxinicity necessary to enrich the sediments in authigenic U. The lack of bioturbation and benthos (with the exception of the single *M. minimus*-covered bedding plane) is further testimony to the anaerobic depositional environment. Hallam (1997, p. 777) has speculated that rapid deepening in the basal Blue Lias produced water depths of no 'more than a few tens of metres at most'. In order to develop a stable, sulphidic lower water column during Paper Shale deposition this estimate should perhaps be considered a minimum. However, the depositional environment was probably within reach of storm wave base as evidenced by the erosive surfaces in the upper part of the Paper Shale (Fig. 7).

The Paper Shale and, to a lesser extent, beds H2 and H3 are affected by syn-sedimentary folding and small growth faults that cause local thickness variations (phase 7). Small normal faults (with centimetre-scale throws) also displace the shale-filled fissures in the uppermost White Lias. The injection of micritic mud along the fault planes in the conglomerate and the presence of micritic dykes in the Paper Shale indicate that not all White Lias strata were lithified by the end of Paper Shale deposition. This phase of extensional tectonic activity appears unique to the basal Blue Lias (no similar features have been reported from higher in the well-studied Blue Lias), and may be the local manifestation of a major tensional event in the southern North Atlantic region (cf. Hallam, 1997, p. 778).

The subsequent history of the basal Blue Lias consists of regular alternations of anoxic, laminated deposition and bioturbated, oxic deposition, that approximately coincides with the lithological alternations, although many limestones are laminated at their bases and tops (Fig. 3). The upward increase of Th/U in successive laminated shales indicates a longer-term trend towards progressively less intense anoxic phases. This trend need not necessarily indicate a shallowing of the depositional event because benthic oxygenation is often observed to improve during the course of a transgression (Wignall, 1994). The predominance of oysters in the aerobic strata has led several workers to suggest that conditions were shallower in the Pre-planorbis Beds than at higher levels within the Blue Lias (Hodges, 1994; Hallam, 1997).

6. DISCUSSION

Proposed sea-level changes during the T–J boundary interval vary greatly. For example, several sequence stratigraphic studies on European basins, reported within the same edited volume (Graciansky *et al.*, 1998), provide remarkably divergent views on eustasy in this interval. Thus, Dumont (1998, p. 627–8) identified a sequence boundary at the base of Pre-planorbis Beds in Tethyan margin sections of southern France, although he noted that evidence for truncation is very rare. In contrast, Goggin & Jacquin (1998) considered the T–J boundary interval in the Paris Basin to be marked by a phase of continuous transgression, as did Jacquin & Graciansky (1998) in their overview of all western European basins. In a study focused on the Jurassic of Britain, Hesselbo & Jenkyns (1998) did not identify a sequence boundary or evidence for sea-level fall in the T–J boundary interval. These views contrast with those of Hallam (1997, 2001) who suggested there was a short-lived, high amplitude regressive–transgressive event at the White Lias/Blue Lias contact. The new exposures in Pinhay Bay lend credence to this interpretation. The topmost beds of the White Lias record a cessation in deposition, marked by the formation and partial erosion of a marine hardground, followed by lithification and subsequent subaerial exposure and dissolution. Finally, a rapid transgression led to the establishment of a stable, euxinic environment. That this regressive–transgressive event cannot be detected in the subsurface record of the Paris Basin (cf. Goggin & Jacquin, 1998), probably reflects its brief duration.

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REFERENCES

COPE, J. C. W., GETTY, T. A., HOWARTH, M. K., MORTON, N. & TORRENS, H. S. 1980. *A correlation of Jurassic rocks in the British Isles, Part One*. Geological Society, London, Special Report, **141**.

DONOVAN, D. T. & KELLAWAY, G. A. 1984. *Geology of the Bristol district: the Lower Jurassic rocks*. Memoir of the British Geological Survey, HMSO, London.

DONOVAN, D. T., HORTON, A. & IVIMEY-COOK, H. C. 1979. The transgression of the Lower Lias over the northern flank of the London Platform. *Journal of the Geological Society, London*, **136**, 165–173.

DUFF, P. McL. D. 1992. Economic geology. In (Duff, P. McL. D. & Smith, A. J.; eds) *Geology of England and Wales*. Geological Society, London, 589–628.

DUMONT, T. 1998 Sea-level changes and early rifting of a European Tethyan margin in the western Alps and southeast France. In (Graciansky, P. C. de, Hardenbol, J., Jacquin, T. & Vail, P. R.; eds) *Mesozoic and Cenozoic sequence stratigraphy of European basins*. SEPM Special Publication, **60**, 623–642.

GEORGE, T. N., HARLAND, W. B. & AGAR, D. V. *et al.* 1969. Recommendations on stratigraphic usage. *Proceedings of the Geological Society of London*, **1656**, 139–169.

GOGGIN, V. & JACQUIN, T. 1998. A sequence stratigraphic framework of the marine and continental Triassic series in the Paris Basin, France. In (Graciansky, P. C. de, Hardenbol, J., Jacquin, T. & Vail, P. R.; eds) *Mesozoic and Cenozoic sequence stratigraphy of European basins*. SEPM Special Publication, **60**, 667–690.

GRACIANSKY, P. C. de, HARDENBOL, J., JACQUIN, T. & VAIL, P. R. 1998. *Mesozoic and Cenozoic sequence stratigraphy of European basins*. SEPM Special Publications, **60**.

HALLAM, A. 1960a. The White Lias of the Devon coast. *Proceedings of the Geologists' Association*, **71**, 47–60.

HALLAM, A. 1960b. A sedimentary and faunal study of the Blue Lias of Dorset and Glamorgan. *Philosophical Transactions of the Royal Society*, **B18**, 1–44.

HALLAM, A. 1981. The end-Triassic bivalve extinction event. *Palaeogeography Palaeoclimatology Palaeoecology*, **35**, 1–44.

HALLAM, A. 1988. A reevaluation of Jurassic eustasy in the light of new data and the revised Exxon curve. In (Wilgus, C. K., Posamentier, H., Ross, C. A. & Kendall, C. G. St. C.; eds) *Sea-level changes: an integrated approach*. SEPM Special Publication, **42**, 261–274.

HALLAM, A. 1990. Correlation of the Triassic–Jurassic boundary in England and Austria. *Journal of the Geological Society, London*, **147**, 421–424.

HALLAM,, A. 1997. Estimates of the amount and rate of sea-level change across the Rhaetian–Hettangian and Pliensbachian–Toarcian boundaries (latest Triassic to early Jurassic). *Journal of the Geological Society, London*, **154**, 773–779.

HALLAM, A. 2001. A review of the broad pattern of Jurassic sea-level changes and their possible causes in the light of current knowledge. *Palaeogeography Palaeoclimatology Palaeoecology*, **167**, 23–38.

HALLAM, A. & EL-SHARAAWY, Z. 1982. Salinity reduction of the end-Triassic sea from the Alpine region into northwestern Europe. *Lethaia*, **15**, 169–178.

HALLAM, A. & WIGNALL, P. B. 1999. Mass extinctions and sea-level changes. *Earth-Science Reviews*, **48**, 217–250.

HART, M. B. 1982. The marine rocks of the Mesozoic. In (Durrance, E. M. & Laming, D. J. C.; eds) *The geology of Devon*. University of Exeter Press, Exeter, 179–203.

HESSELBO, S. P. & JENKYNS, H. C. 1995. A comparison of the Hettangian to Bajocian successions of Dorset and Yorkshire. In (Taylor, P. D.; ed.) *Field Geology of the British Jurassic*. Geological Society, London, 105–150.

HESSELBO, S. P. & JENKYNS, H. C. 1998. British Lower Jurassic sequence stratigraphy. In (Graciansky, P. C. de, Hardenbol, J., Jacquin, T. & Vail, P. R.; eds) *Mesozoic and Cenozoic sequence stratigraphy of European basins*. SEPM Special Publication, **60**, 561–582.

HODGES, P. 1994. The base of the Jurassic System: new data on the first appearance of *Psiloceras planorbis* in southwest Britain. *Geological Magazine*, **131**, 841–844.

JACQUIN, T. & GRACIANSKY, P.-C. de 1998. Major transgressive/regressive cycles: the stratigraphic signature of European basin development. In (Graciansky, P.-C. de, Hardenbol, J., Jacquin, T. & Vail, P. R.; eds) *Mesozoic and Cenozoic sequence stratigraphy of European basins*. SEPM Special Publication, **60**, 15–30.

LANG, W. D. 1924. The Blue Lias of the Devon and Dorset coasts. *Proceedings of the Geologists' Association*, **35**, 169–185.

MYERS, K. J. & WIGNALL, P. B. 1987. Understanding Jurassic organic-rich mudrocks – new concepts using gamma-ray spectrometry and palaeoecology: examples from the Kimmeridge Clay of Dorset and the Jet Rock of Yorkshire. In (Leggett, J. K. & Zuffa, G. G.; eds) *Marine clastic sedimentology*. Graham & Trotman, London, 172–189.

POOLE, E. G. 1979. The Triassic–Jurassic boundary in Great Britain. *Geological Magazine*, **116**, 303–311.

RICHARDSON, L. 1906. On the Rhaetic and contiguous deposits of Devon and Dorset. *Proceedings of the Geologists' Association*, **19**, 401–409.

RICHARDSON, L. 1911. The Rhaetic and contiguous deposits of West, Mid and part of East Somerset. *Quarterly Journal of the Geological Society, London*, **67**, 1–74.

SELLWOOD, B. W., DURKIN, M. K. & KENNEDY, W. J. 1970. Field meeting on the Jurassic and Cretaceous rocks of Wessex. *Proceedings of the Geologists' Association*, **81**, 715–732.

SWIFT, A. 1995. A review of the nature and outcrop of the 'White Lias' facies of the Langport Member (Penarth Group: Upper Triassic) in Britain. *Proceedings of the Geologists' Association*, **106**, 247–258.

SWIFT, A. 1999. Stratigraphy (including biostratigraphy). In (Swift, A. & Martill, D. J.; eds) *Fossils of the Rhaetian Penarth Group*. Field Guides to Fossils, **9** Palaeontological Association, London, 15–30.

TORRENS, H. S. & GETTY, T. A. 1998. The base of the Jurassic system. In (Cope, J. C. W., Getty, T. A., Howarth,

M. K., Morton, N. & Torrens, H. S.; eds) *A correlation of Jurassic rocks in the British Isles*. Geological Society, London, Special Report, **14** 17–22.

WARRINGTON, G., COPE, J. C. W. & IVIMEY-COOK, H. C. 1994. St. Audrie's Bay, Somerset, England: a candidate Global Stratotype Section and Point for the base of the Jurassic system. *Geological Magazine*, **131**, 191–200.

WIGNALL, P. B. 1994. *Black shales*. Oxford University Press, Oxford.

WILKIN, R. T., BARNES, H. L. & BRANTLY, S. L. 1996. The size distribution of framboidal pyrite in modern sediments: An indicator of redox conditions. *Geochimica et Cosmochimica Acta*, **60**, 3897–3912.

WOODWARD, H. B. 1889. Preliminary excursion to Lyme Regis. *Proceedings of the Geologists' Association*, **11**, xxvi–xlix.

WOODWARD, H. B. 1906. Excursion to Lyme Regis Easter 1906. *Proceedings of the Geologists' Association*, **19**, 320–340.

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