THE STRATIGRAPHY OF THE PENARTH GROUP (LATE TRIASSIC) OF THE EAST DEVON COAST

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Gallois, R.W. 2007. The stratigraphy of the Penarth Group (late Triassic) of the east Devon coast.
Geoscience in south-west England, **11**, 287-297.

The cliff and foreshore exposures in the Devon part of the Dorset and East Devon Coast World Heritage Site expose an unbroken late Triassic to early Jurassic succession. The change from the terrestrial, red-bed facies of the Triassic Mercia Mudstone Group to the fully marine conditions of the Jurassic Lias Group takes place via the Penarth Group, a succession of mudstones, siltstones and limestones deposited in lagoonal and sheltered shallow-marine environments of varying salinities. The Penarth Group as currently defined is divided into the Westbury Formation overlain by the Lilstock Formation, based on type sections in the Severn Estuary area. The lithology and sedimentology of the Westbury Formation strata exposed on the east Devon coast are closely comparable with those of the type area, but those of the Lilstock Formation are not. It is therefore proposed on lithological and historical grounds that this formation should be replaced by a Cotham Formation overlain by a White Lias Formation. This would reinstate, without any change in their original definitions, two of the oldest formally defined stratigraphical names in the British Phanerozoic. All three formations are lithologically distinctive, and are separated from their neighbours by erosion surfaces that represent non-sequences. Those at the bases of the Westbury and Cotham formations are overlain by pebble beds rich in vertebrate remains ('bone beds'). The Cotham Formation is a highly condensed succession comprised of thinly interbedded mudstones and limestones with ripple trains, stromatolites, desiccated surfaces and slumped beds, the last of which have been attributed to earthquakes or a bolide impact. The limestones of the White Lias Formation exposed on the east Devon coast are sedimentologically complex with channels, slumps and desiccated surfaces. The position of the Triassic-Jurassic boundary is currently under review. Possible positions include the base of the Cotham Formation, a horizon within the formation, the base of the White Lias, the base of the overlying Blue Lias Formation or a horizon within the Blue Lias Formation.

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INTRODUCTION

The Triassic rocks of southern England were divided by Warrington *et al.* (1980) into groups on the basis of gross lithology (Table 1). In ascending order the Sherwood Sandstone Group (pebble beds and sandstones), Mercia Mudstone Group (mudstones and silty mudstones) and Penarth Group (thinly interbedded mudstones, limestones and sandstones). At the base of the succession the unfossiliferous Aylesbeare Group (predominantly mudstones), a name adopted from Smith *et al.* (1974), was thought at that time to encompass the Permian-Triassic boundary but is now thought to be largely Triassic in age.

In southern England the Penarth Group sediments mark a transition from the hot deserts of the Permo-Triassic that had lasted for over 100 million years, to the predominantly marine sedimentation of the Jurassic-Cretaceous that was to last for another 135 million years. The group comprises thinly interbedded mudstones, siltstones and limestones that were deposited in lagoonal and restricted-marine environments that ranged from slightly saline to fully marine. The succession is highly condensed, contains numerous sedimentary breaks, and is bounded by erosion surfaces that can be traced throughout south-west England. It represents about 3 million years of sedimentation that span the mid and late Rhaetic Stage.

The most complete extant exposures of the Penarth Group in Britain are cliff and foreshore outcrops on the south Wales coast around Penarth, on the north Somerset coast between Watchet and Lilstock, and on the Devon coast (Figure 1). The cliffs of the east Devon coast contain the most complete exposures of the Triassic succession in the British Isles, and the best exposure of the terrestrial facies in Europe. The succession dips steadily eastwards, mostly at 01° to 03°, and is overlain with marked unconformity by an almost horizontal sheet of mid-Cretaceous Gault and Upper Greensand formations with the result that the Triassic rocks are overstepped in a westerly direction (Gallois, 2006). The Penarth Group outcrop is confined to the most easterly part of the coast where it is exposed on the foreshore and in cliffs 400 m W of Culverhole Point [272 893] (referred to here as Culverhole), at Charton Bay [SY 299 899 to 302 900] and at Pinhay Bay [SY 313 903 to 321 908]. The full thickness of the group was proved in the Lyme Regis (1901) Borehole [SY 3361 9299] (Warrington and Scrivener, 1980) and the Charmouth No. 16 Borehole [SY 3656 9308] (Ivimey-Cook, 1973; Warrington, 2005), *c.* 3 and *c.* 5 km NE of Pinhay Bay respectively, and in hydrocarbon-exploration boreholes throughout the Wessex Basin (Lott *et al.*, 1982).

Group	Type section/area	Thickness, type area	Thickness, east Devon
Penarth	Penarth, South Wales	16 m	18 m
Mercia Mudstone	East Devon coast	450 m	450 m
Sherwood Sandstone	Sherwood Forest, Notts	up to 400 m	180 m
Aylesbeare	East Devon coast	500 m*	500 m

Table 1. *Component groups of the Triassic rocks of the British Isles (after Warrington* et al.*, 1980). *lowest part possibly Permian.*

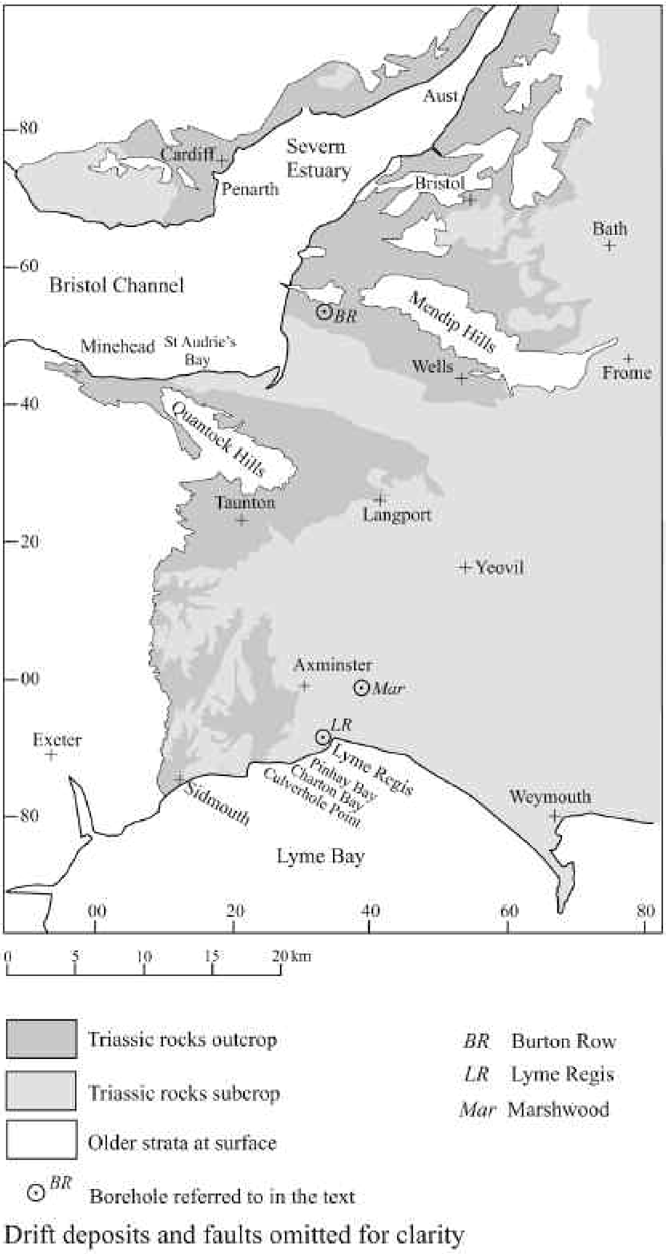

Figure 1. *Distribution of the Penarth Group in south-west England showing the positions of outcrops and boreholes referred to in the text.*

Proposed revision of the Penarth Group nomenclature

The position of the Triassic-Jurassic boundary has long been the subject of debate. De la Beche (1839) regarded the *Avicula contorta* Shales (subsequently the Westbury Beds of Wright, 1860) and the overlying White Lias of William Smith (1797) as the oldest formations of the Jurassic (Table 2). Oppel (1856-58) correlated the faunas of the *Avicula contorta* Shales with those of the late Triassic Keuper Stage and those of the White Lias with those of the Jurassic Hettangian Stage of Germany. Moore (1861) correlated both faunal assemblages with those of the newly defined Rhaetian Stage, which at that time was taken to be the oldest stage of the Jurassic. One result of this was that the lithological name Rhaetic Beds came to be used for this group of strata on the Geological Survey maps from that time onwards. The base of the Jurassic System was subsequently changed to be the base of the Hettangian Stage (Arkell, 1956) and the Rhaetian Stage, and by implication the Rhaetic Beds, returned to the Triassic.

The Rhaetic Beds of the earlier British Geological Survey (BGS) maps were renamed the Penarth Group by Warrington *et al*. (1980) in the Geological Society's report on the correlation of the Triassic rocks in the British Isles, with a type section in the cliffs at Penarth, South Wales (Figure 1). This section is close to the margin of the Triassic basin of deposition and consequently atypical in terms of lithologies and thicknesses of most of the Rhaetic Beds at outcrop. The Penarth Group was divided into two formations, the Westbury Formation and an overlying Lilstock Formation with a type section on the north Somerset coast. The latter combined the Cotham Beds of Richardson (1911) and all the beds between the top of the Cotham Beds and the 'top of the Penarth Group (=top of the Lilstock Formation)' (Warrington *et al*., 1980, p. 60). Put simply, the top of the Lilstock Formation was defined as the top of the Lilstock Formation.

Formations are defined by their bases and the top of the Lilstock Formation is therefore defined by the base of the overlying Blue Lias Formation. In contrast to the Triassic report, the authors of the Jurassic report (Cope *et al*., 1980) retained William Smith's (1797) Blue Lias and his definition of its base. In the Bath-Bristol area where he first decribed it, this is a sharp upward change from the white limestones of the White Lias to laminated organic-rich mudstones of the Blue Lias. The boundary is marked throughout south-west England by an erosion surface with numerous well-preserved *Diplocraterion* burrows that descend up to 0.5 m into the limestone. This burrowed bed was called the Sun Bed by the quarrymen of the Bath area, a

Wm Smith, 1797; 1815	De la Beche, 1839; Richardson, 1911	BGS maps pre-1980		Warrington *et al*., 1980		This account
Blue Lias	Blue Lias	Blue Lias		Blue Lias Fm		Blue Lias Fm
White Lias	White Lias	Rhaetic Beds	White Lias	Lilstock Fm	Langport Mbr	White Lias Fm
Indigo and Black Marls	Cotham Beds		Cotham Beds		Cotham Mbr	Cotham Fm
	A. contorta Shales		Westbury Beds	Westbury Fm		Westbury Fm
Red Ground	Keuper Marl	Keuper Marl		Blue Anchor Fm		Blue Anchor Fm

Fm = Formation Mbr = Member

Table 2. *Evolution of the nomenclature of the latest Triassic and earliest Jurassic succession in south-west England.*

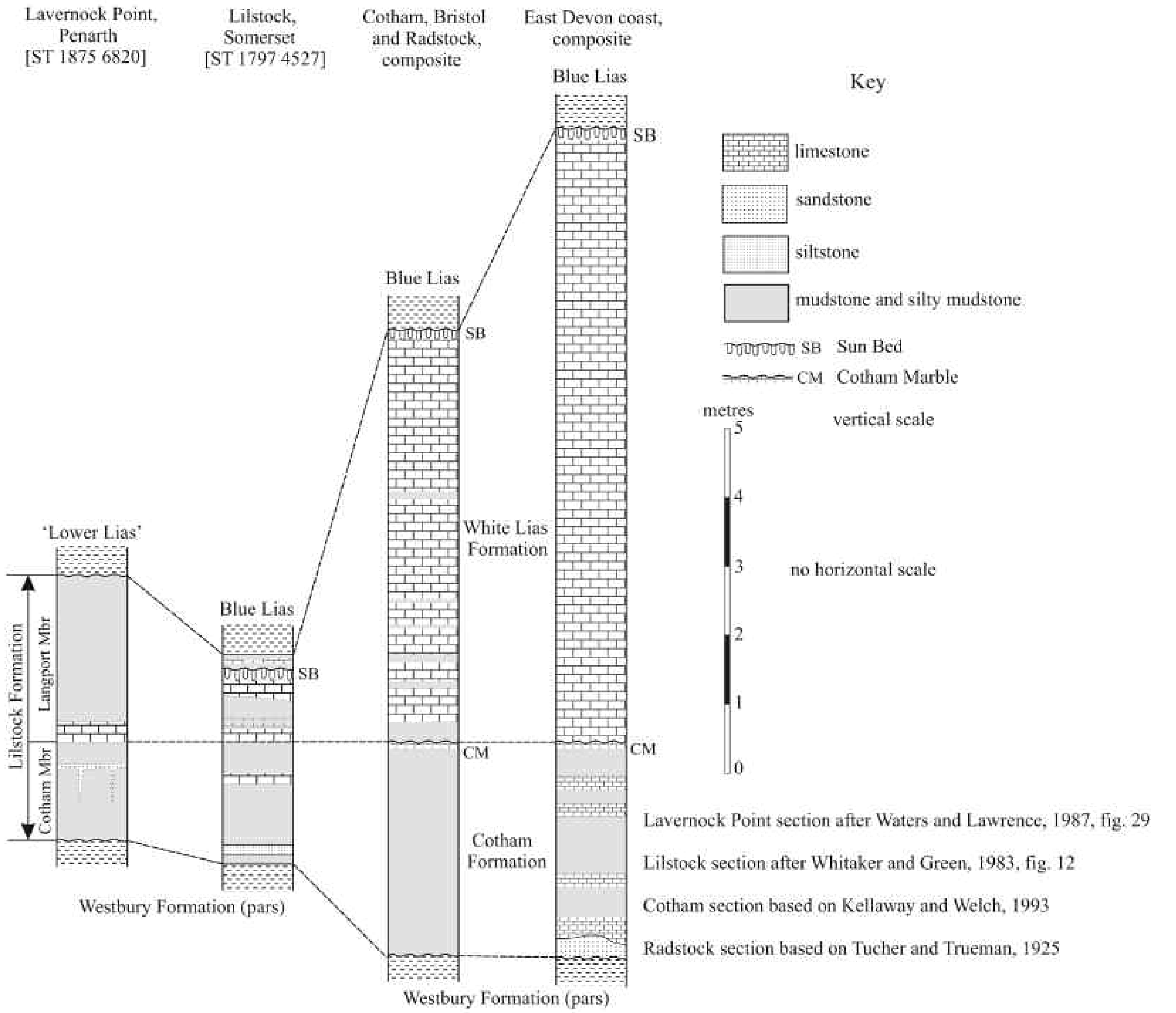

Figure 2. *Correlation of the Lilstock Formation succession of the type area with that of the Penarth Group type area and those of the Bristol-Bath area and the east Devon coast. See text for details.*

name that has been adopted by geologists. The junction of the White Lias and Blue Lias is one of the most distinctive and easily recognised boundaries in the British Phanerozoic, at outcrop and in the subcrop.

William Smith's definition of the base of the Blue Lias has been shown to be valid throughout south-west England except for the atypical areas of sedimentation in the Penarth and Lilstock areas (Figure 2). There, the erosion surface at the top of the White Lias is overlain by mudstones that were named the Watchet Beds by Richardson (1911). These were included in the Blue Lias by Whitaker (1978) and in the Lilstock Formation by Warrington *et al.* (1980).

On the east Devon coast and throughout most of its outcrop in south-west and southern England the Penarth Group as currently defined comprises three lithologically distinct units, each of which is separated from its neighbours by a widespread erosion surface that represents a sequence boundary (Figure 3). These are, in ascending order, the dark grey mudstones of the Westbury Formation, thinly interbedded green mudstones and limestones of the former Cotham Beds, and the limestones of the White Lias. Each is lithologically distinctive from its neighbours, and each is a mappable unit. It is therefore proposed here that they should have formation status.

The Westbury Formation at outcrop throughout south-west England and South Wales consists of dark grey, fossiliferous, pyritic, relatively weak mudstones that weather to an almost black, sticky clay that gives rise to small-scale landslips and hill creep. As a result, it is poorly exposed even in the coastal sections. The base of the formation is taken at the base of a gritty or pebbly mudstone that rests with marked colour contrast at most localities on an erosion surface cut into the Blue Anchor Formation mudstones. The original type section in Garden Cliff at Westbury-on-Severn area is now degraded and has been replaced by reference sections in the cliffs near Lavernock Point [ST 187 682] and at St Mary's Well Bay [ST 175 177] in the Penarth area (Warrington *et al.*, 1980).

The Cotham Beds were named after Cotham Park, Bristol with a now-defunct type section in the adjacent Clifton area (Richardson, 1911). Warrington *et al.* (1980) proposed type sections at Lavernock Point and Lilstock, Somerset [ST 177 454] and to these should be added supplementary sections at St Audrie's Bay, Somerset [ST 104 431] (Mayall, 1979; Hesselbo *et al.*, 2004) and Culverhole. The definition of the base of the proposed Cotham Formation is the same as that for the Cotham Member which it replaces. The formation rests non-sequentially with sharp lithological contrast on an eroded surface cut in the Westbury Formation. At all the reference sections and most localities in south-west England the basal bed of the Cotham Formation is a sandy, locally pebbly, remanié deposit, rich in finely comminuted fish and other vertebrate debris.

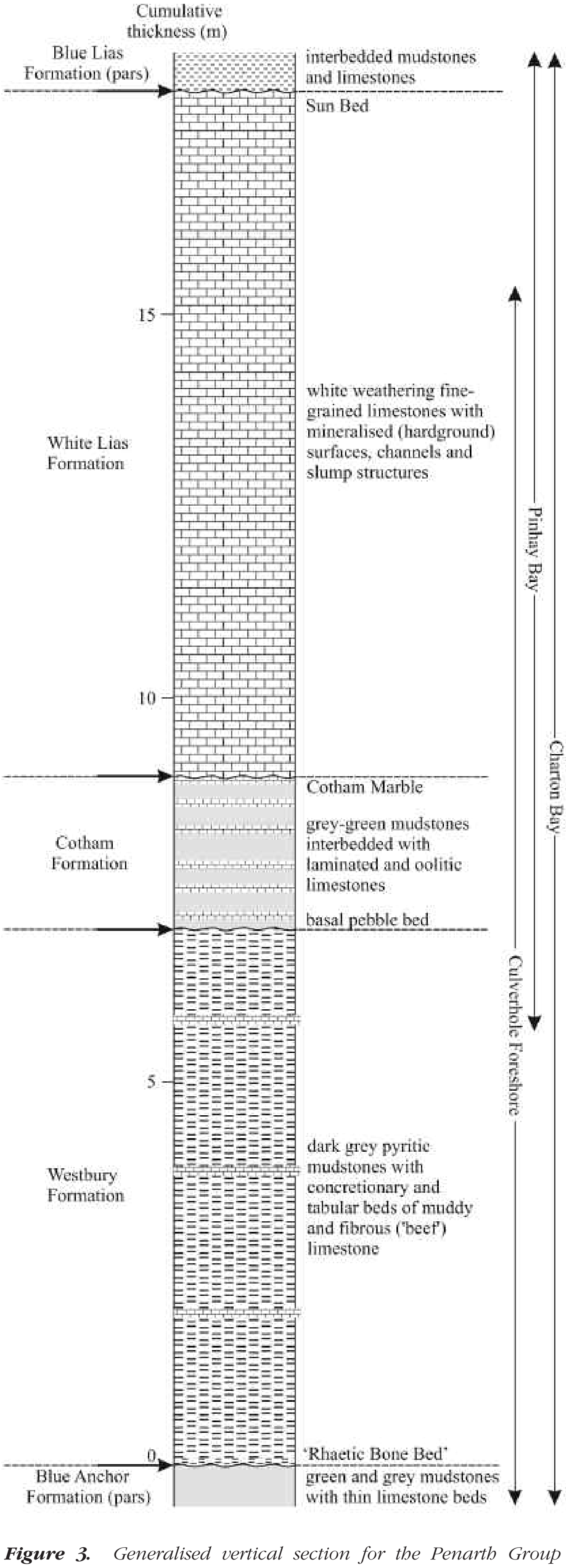

Figure 3. *Generalised vertical section for the Penarth Group succession exposed on the east Devon coast.*

The most complete section recorded to date is that at Culverhole where there is a record of relatively continuous, albeit highly condensed, sedimentation. The successions exposed on the Somerset and South Wales coasts can all be divided into a lower and an upper part, separated by a prominent desiccated surface that probably represents a major break in sedimentation (Figure 2). The Cotham Marble forms a lithologically distinctive marker bed at the top of the formation in every section recorded to date in Avon, Devon and Somerset, and a few authors have also recorded it on the South Wales coast (e.g. Mayall, 1979).

The characteristic pale-weathering limestones of the White Lias Formation form a marker bed that can be recognised at outcrop throughout south-west England and the Midlands as far north as Nottinghamshire (Swift, 1995), and in the subcrop throughout southern England by virtue of its strong seismic-reflection signal (Lott *et al.*, 1982). It is one of the oldest proper names in geology and describes one of the most lithologically distinctive rocks in the European stratigraphical succession.

In its original type area in the Bath-Radstock region of Somerset, the White Lias consists of 4 to 6 m of limestone with a few mudstone partings (Donovan and Kellaway, 1964) (Figure 2). On the Devon coast it consists of up to 9 m of limestone.

The quarries at Langport, from which the Langport Member takes its name, have long since become degraded and the proposed substitute type section for the member at Lilstock is lithologically atypical of the White Lias. The type section for the proposed White Lias Formation is the cliff [SY 3177 9080 to 3220 9085] at Pinhay Bay with reference sections at Charton Bay [SY 3004 9005] and Culverhole [SY 2734 8935]. At these localities the basal bed of the formation is a calcareous mudstone or limestone that rests with an erosional contact on an irregular surface cut into the Cotham Formation. The erosion surface rests on patches of Cotham Marble, accumulations of brecciated Cotham Marble ('Crazy Cotham') or, where these are absent, on a bored and solution affected laminated limestone pavement. The sections on the Somerset and South Wales coasts, where the presumed equivalent of William Smith's White Lias is highly attenuated and lithologically markedly different from the White Lias of the Bath and east Devon areas, are unsuitable as reference sections (Figure 2). At its type section at Lilstock, Somerset [ST 177 451], the Langport Member consists of 0.25 to 0.35 m of porcellanous limestone overlain by 0.9 m of thinly interbedded limestone and marl.

Not only were the type sections of the Penarth Group and Lilstock Formation poorly chosen, so also was the basal boundary of the group. The principle upward lithological change in the late Trias from terrestrial red beds to green and grey mudstones with limestones that represent more fluvial environments takes place within the Mercia Mudstone Group at the base of the Blue Anchor Formation. This lithological change is particularly well displayed in the cliffs at St Audrie's Bay and Charton Bay. Detailed discussion of the reasons why the base of a redefined 'Penarth Group' should be taken at the base of the Blue Anchor Formation are beyond the scope of this paper, but consideration should be given to defining the beds between the red beds of the Mercia Mudstone Group and the marine sediments of the Lias Group as a new group. The type section of the group should be on either the Devon or Somerset coast where the successions are more complete than those at Penarth.

PENARTH GROUP OF THE EAST DEVON COAST

Westbury Formation

The full thickness of the formation was exposed in a low cliff [275 893] near Culverhole Point in the 19th century, but this was subsequently covered by landslip debris. The base of the Westbury Formation, in the form of burrow infillings that penetrate the top of the Blue Anchor Formation, is exposed in the intertidal areas at Charton Bay [281 893] (Figure 4A) and Pinhay Bay [SY 319 908]. Sections in the higher part of the

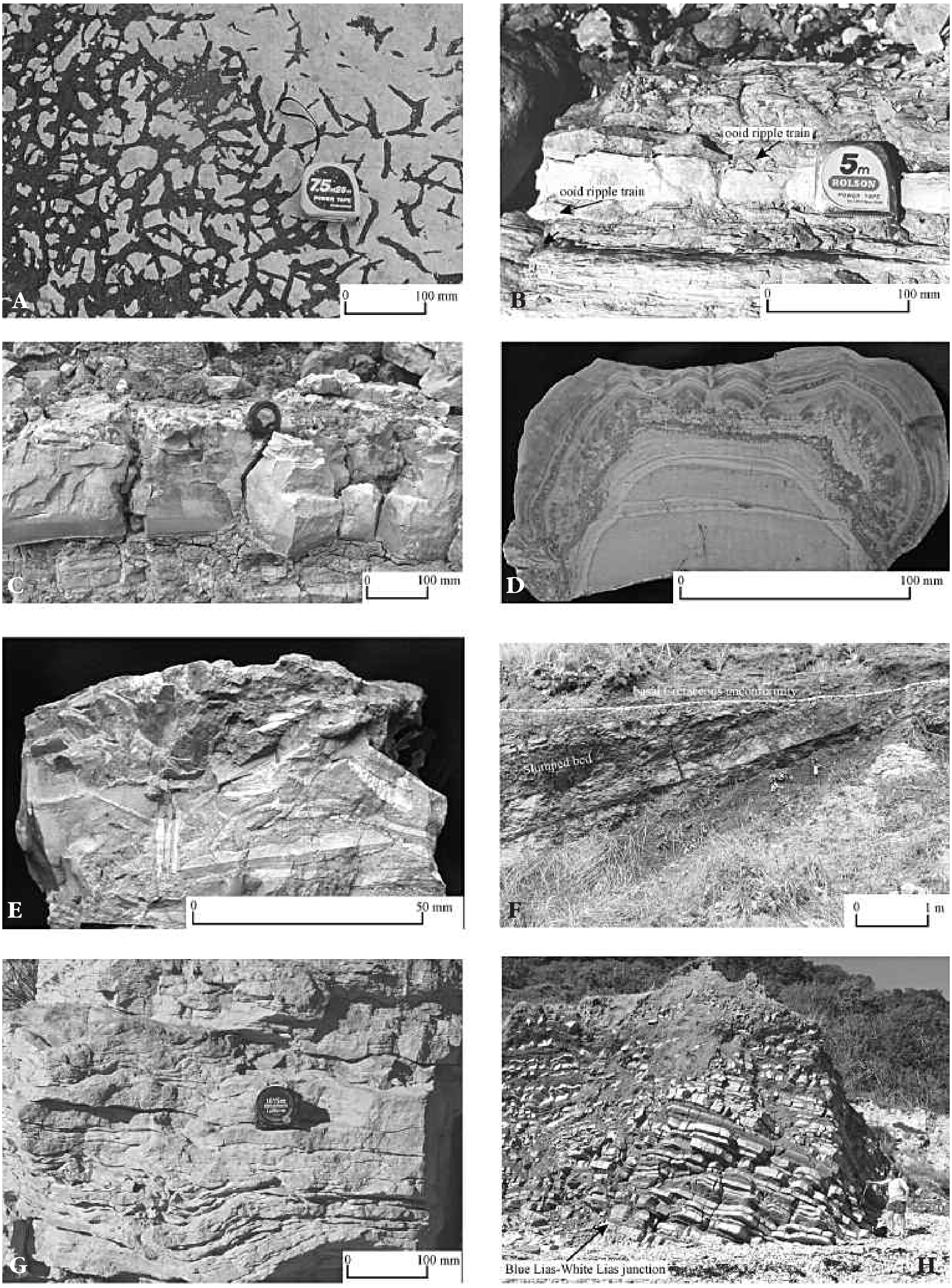

Figure 4. *Selected Penarth Group lithologies exposed on the east Devon coast.* ***A*** *Unconformable junction of the Westbury Formation and Blue Anchor Formation on Charton Foreshore. Burrows infilled with dark grey mudstone and angular green mudstone clasts extend down into the top bed of the Blue Anchor Formation.* ***B*** *Cotham Formation limestones and mudstones exposed at Culverhole.* ***C*** *Highest beds of the Cotham Formation at Culverhole. The tape rests on a penecontemporaneously solution affected and bored laminated limestone at the top of the formation.* ***D*** *Stromatolithic Cotham Marble: part of small dome growing on laminated fine-grained limestone. Found loose on Charton Foreshore by Professor Bruce Sellwood, University of Reading. Probably the same laminated limestone as that shown in C.* ***E*** *Crazy Cotham, loose block from Culverhole. Pale, angular laths of laminated stromatolitic limestone are embedded in a micrite matrix.* ***F*** *White Lias at Culverhole: channel in fine-grained limestones in the top part of the formation infilled with clast-rich slumped beds in a micrite matrix.* ***G*** *Detail of slump and possible dewatering structures in fine-grained limestones in the White Lias at Culverhole.* ***H*** *White Lias-Blue Lias junction exposed in a fault block at Charton Bay.*

formation, including the junction with the Cotham Formation, are exposed in the intertidal area at Culverhole when the beach shingle is low. The full succession of the formation has probably been exposed at some time at the eastern end of Charton Bay [SY 300 900], but there is no published description of the succession there and the sections now consist of patches of deeply weathered clay that are disturbed by hill creep.

The Westbury Formation exposed at Charton and Pinhay bays rests with marked lithological contrast and sedimentary break on green silty mudstones of the Blue Anchor Formation. On the Somerset coast, Mayall (1981) described a Williton Member at the top of the Blue Anchor Formation. This has not been recorded in Devon and is presumed to have been removed by erosion at the base of the Westbury Formation. Samples from the upper part of the Blue Anchor Formation outcrop adjacent to Culverhole Point have yielded, organic-walled microplankton, foraminifers, and palynomorphs indicate of a Rhaetian age (Warrington, 2005). This age determination is supported by a study by Hounslow *et al.* (2001) who showed that the Blue Anchor Formation of the Somerset coast has a predominantly reversed magnetopolarity that can be correlated with a long reversed interval in the Rhaetian part of the Newark Supergroup of the eastern USA.

Woodward and Ussher (1911) recorded a complete section through the Westbury and Cotham formations in a cliff about 100 m W of the present-day exposures at Culverhole in 1884. Richardson (1906) and Mayall (1979) measured sections through the full thickness of the formation in the same area, 5.2 m and 6.5 m thick respectively, but neither of these is now visible. The Westbury Formation consisted of fossiliferous black shales with a pebbly calcareous grit at the base that contained reptilian bones, fish-remains and coprolites. Specimens from Culverhole in the British Geological Survey (BGS) collections examined by Ivimey-Cook (1993) include *Acrodus* sp., *Saurichthys* sp., *Gyrolepis alberti* Agassiz, *Chlamys valoniensis* (Defrance) and *Protocardia rhaetica* (Merian) from the basal pebble/bone bed, and *Chlamys, Pecten, Protocardia, Pteria, 'Schizodus'* and small gastropods from the overlying mudstones. In addition to the above, Ivimey-Cook (1993) recorded *Eotrapezium concentricum* (Moore), *Lyriomyophoria postera* (Quenstedt), *Rhaetavicula contorta* (Portlock), *'Natica' oppeli* Moore, *Cardinia* sp., *Cercomya* sp., *Dimyopsis [Atreta] intusstriata* (Emmrich), *Modiolus hillanoides* (Chapuis & Dewalque), *'Modiolus' sodburiensis* Reynolds & Vaughan, *Placunopsis alpina* (Winkler) and *Tutcheria cloacina* (Quenstedt) in the upper part of the Westbury Formation in the Charmouth No. 16 Borehole.

The pebble bed at the base of the Westbury Formation, the correlative of the 'Rhaetic Bone Bed' of the Somerset and Severn Estuary areas, was well known to Mary Anning and other early fossil collectors, but in recent years has only been regularly exposed at Charton Bay. It sits on an irregular, intensely burrowed erosion surface cut in the Blue Anchor Formation mudstones (Figure 4A). The exposures consist mostly of concentrations of pebbly grey mudstone in desiccation cracks, burrow fills and shallow scour hollows (<20-30 mm deep) that penetrate the top 300 mm of the Blue Anchor mudstones. The mudstones contain finely disseminated silt- and sand-grade vertebrate remains, small (mostly <5 mm) angular clasts of the underlying green mudstone, and abundant silt- and sand-grade clear quartz. Many of the larger quartz grains are well rounded and frosted and appear to have been derived from a desert environment. The fish assemblage is similar to, but more diverse than, that of the bone bed at Westbury on Severn and other localities in Avon and contains two genera of bony fish, *Dapedium* and *Lepidotes*, not previously recorded from the Rhaetic Bone Bed (Mike Curtis *personal communication*, 2006).

The fauna of the Westbury Formation is dominated by thin-shelled bivalves that are indicative of quiet-water, brackish and marine environments. Open-marine forms such as ammonites and brachiopods have not been reported. Thomas *et al.* (1992) concluded from a study of the distribution of methyl steranes (alkane biological markers) in the Blue Anchor and Westbury formations of the Somerset coast that the Blue Anchor Formation was deposited in a supratidal sabkha setting and the Westbury Formation in marginal marine environments. This interpretation was supported by Tuweni and Tyson (1994) who concluded that the organic fractions of the Westbury Formation mudstones of the Somerset coast were deposited in marginal-marine environments that were distant from fluvial sources of organic matter.

Cotham Formation

A complete section through the Cotham Formation *c.* 3.1 m thick was exposed on Culverhole Foreshore in 1997 for a short time after a storm, but parts of this have been covered by beach deposits since that time. The succession rests on a dessicated surface of Westbury Formation mudstones with a bone-rich pebble bed at its base. This is overlain by up to 2.8 m of thinly and complexly interbedded sandstones, grey and greenish grey mudstones and laminated or nodular limestones, within which there are several lithologically distinctive beds including slumps, dewatering structures, ooid ripple trains (Figure 4B) and stromatolitic beds (Figure 5). The most prominent of the last named is the Cotham Marble (= 'Landscape Marble') at the top of the formation (Figure 4C). This forms a lithologically distinctive marker bed that can be recognised throughout the Somerset and Bristol areas. Blocks of 'Cotham Marble' (Figure 4D) up to 0.2 m thick and its broken and re-sedimented correlative 'Crazy Cotham', have been recorded loose at Culverhole and at Charton Bay (Sellwood *et al.*, 1970).

Richardson (1906) recorded about 1.8 m of Cotham Formation, including the junction with the Westbury Formation and the Cotham Marble, in a cliff and foreshore about 100 m W of the modern exposures at Culverhole, but this was subsequently destroyed by a landslip. The beds above the Cotham Marble in Richardson's section contain greenish grey mudstones, a Cotham Formation lithology, which suggests that the section was disturbed by faulting or landslip. Woodward and Ussher (1911) recorded a section in this or an adjacent cliff in which 0.2 m of lenticular Cotham Marble rested directly on fossiliferous Westbury Formation black shales. This too was presumably either faulted or disturbed by landslip.

Mayall (1979, figure 7.2) recorded what was described as a complete section through the Cotham Formation at Culverhole, but this was only 1.6 m thick. It includes beds that are the correlatives of some of those in the lower and middle parts of the section shown in Figure 5, including the slumped Bed 3, the stromatolitic Bed 5, the oolitic beds 7 and 9 and the Cotham Marble. The sandy beds 1 and 2 and the limestone beds 11, 12, 14 and 16 are absent from Mayall's section. The Cotham Formation at Culverhole and elsewhere in south-west Britain contains a sparse bivalve fauna that includes *Chlamys* and *Eotrapezium* together with the branchiopod *Euestheria*, the ostracod *Darwinula* and the bryophyte *Naiadita*. The last three are indicative of deposition in brackish water.

The lithologies exposed at Culverhole are similar to those of the Cotham Formation exposed on the Somerset (Whitaker and Green, 1983) and South Wales (Waters and Lawrence, 1993) coasts, but the successions in these areas are thinner (mostly < 1.5 m) and the order in which the lithologies occur differs in detail. In a study of the Cotham Formation in South Wales, Somerset and east Devon, Mayall (1983) correlated slumped beds in the lower part of the formation in all three areas with one another and concluded that they were probably caused by a seismic shock. The overall sequence of lithologies in these areas is sufficiently similar to suggest that some of the slumped beds might be contemporaneous, but there is no palaeontological or other evidence to confirm this. The presence of slumped horizons at Culverhole in the underlying Blue Anchor Formation and in the overlying White Lias (see below) that are not present in the correlative strata elsewhere in Devon, Somerset or South Wales, suggests that other, more local causes might be responsible.

The shock-wave theory was extended by Simms (2004) who correlated slumped beds in the Cotham Formation throughout the UK with one another and concluded that they resulted from a major bolide impact 600 km W or NW of central Britain. He also recognised a 'tsunamite' deposit resting on the 'seismite' and concluded that it was formed by the tidal wave that the impact had produced. None of the sediments in the Cotham Formation exposures on the east Devon, Somerset and South Wales coasts requires an extra-terrestrial explanation. In all three areas the presence of slumps, dewatering structures, ripples, ooids, cross bedding, lamination, desiccation surfaces and stromatolites can be explained in terms of processes that occur in shallow-water lagoonal and intertidal environments.

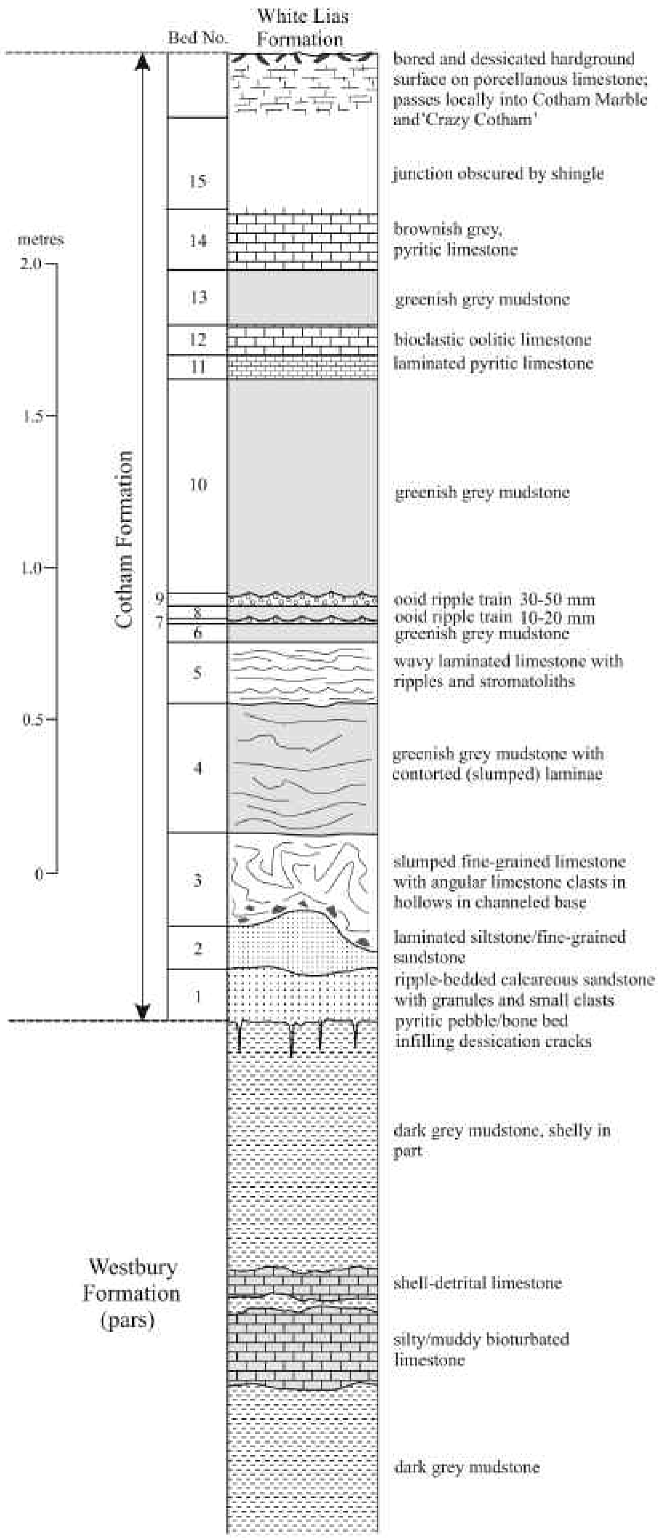

Figure 5. *Cotham Formation succession exposed at Culverhole.*

White Lias Formation

On the east Devon coast the Cotham Formation is overlain by up to 9 m of fine-grained, White Lias limestone which was formerly extensively worked for building and agricultural purposes in Devon and Somerset. Hallam (1960) described the cliff sections at Pinhay Bay [SY 3177 9080 to 3220 9085] as 'incomparably the best section in the country'. The sections at Charton Bay [SY 3004 9005] and Culverhole Foreshore [SY 2734 8935] can arguably be described as the second and third best sections, although the latter is less complete due to the westerly overstep of the Upper Greensand. Taken together, they are the only sections in south-west England that enable the sedimentology and lateral variations within the formation to be studied in detail.

At the present time, the cliffs at Pinhay Bay and Charton Bay expose the upper 7.0 m and 7.2 m of White Lias respectively, including the junction with the Blue Lias. Hallam (1960) recorded 7.84 m at Pinhay Bay from which *c.* 1 m of the basal beds and the junction with the Cotham Formation were missing. A low sea-cliff at Culverhole exposes the full preserved thickness of the formation including the junction with the Cotham Formation and the Upper Greensand. The base of the formation has also been exposed from time to time on the foreshore at Pinhay Bay, but in recent years the lowest *c.* 2 m and the junction with the Cotham Beds has been covered by beach deposits. The only description of the complete succession there is that of Mayall (1979) who recorded 8.0 m of limestone. Woodward and Ussher (1911) noted that the whole of the White Lias was exposed from time to time at Charton Bay and Richardson (1906) recorded 5.8 m of White Lias there including the junction with the Blue Lias. He estimated the total thickness to be 7.6 m. At Culverhole, the base of the formation is marked by an irregular erosion surface with fine-grained limestone resting with marked lithological contrast on either Cotham Marble or a bored and solution-affected limestone surface (Figure 4E).

The predominant lithology of the White Lias in Devon is off-white, fine-grained limestones (calcilutites) with complex sedimentary structures including channels, slumps and hardground surfaces. Hallam (1968) recorded slumped horizons that he attributed to earthquake activity, intraformational conglomerates, and sun-cracked and bored surfaces indicative of emergence above sea level. To these can be added irregular solution affected surfaces that may indicate dissolution by meteoric waters and broad, intersecting channels with and without slumped margins.

The formation is sparsely fossiliferous at most stratigraphical levels, but winnowed concentrations of shells are locally present at a few horizons. These include bivalves, brachiopods, gastropods, serpulids and rare corals indicative of deposition in quasi-marine to fully marine environments. The faunas from the Charton, Culverhole and Pinhay Bay exposures in the BGS collections include serpulid tubes, the coral cf. *Oppelismilia*, the bivalves *Astarte* sp., *Chlamys (C.) pollux* (d'Orbigny), *Eotrapezium concentricum* (Moore), *Eotrapezium ewaldi* (Borneman), *Eotrapezium* sp., *Gervillia praecursor* (Quenstedt), *Gervillia* sp., *Grammatodon lycetti* (Moore), *Liostrea hisingeri* (Nilsson), *Lucina* sp., *Modiolus hillanoides* (Chapius & Dewalque), *Modiolus* sp., *Pleuromya*?, *Pronoella*?, *Protocardia* sp.and *Pteromya*?, the gastropods *Bourguetia* sp, *Procerithium* sp. *'Chemnitzia'* cf. *nitida* Moore, and echinoid spines (Ivimey-Cook, 1993).

The upper two thirds of the formation is wholly exposed at Pinhay and Charton bays where the burrowed junction with the Blue Lias is well displayed. The current sections are graphically summarised in Figure 6. The rapid lateral variations in the successions at both localities make it difficult to correlate the sections in detail with one another or with Hallam's (1960) published section. With the exception of the Sun Bed, which is common to all three sections, the only obvious correlation is the 'main slump bed' (Hallam's Bed No. 8 = Bed 9 in Figure 6). The most accessible and clean section for the study of the

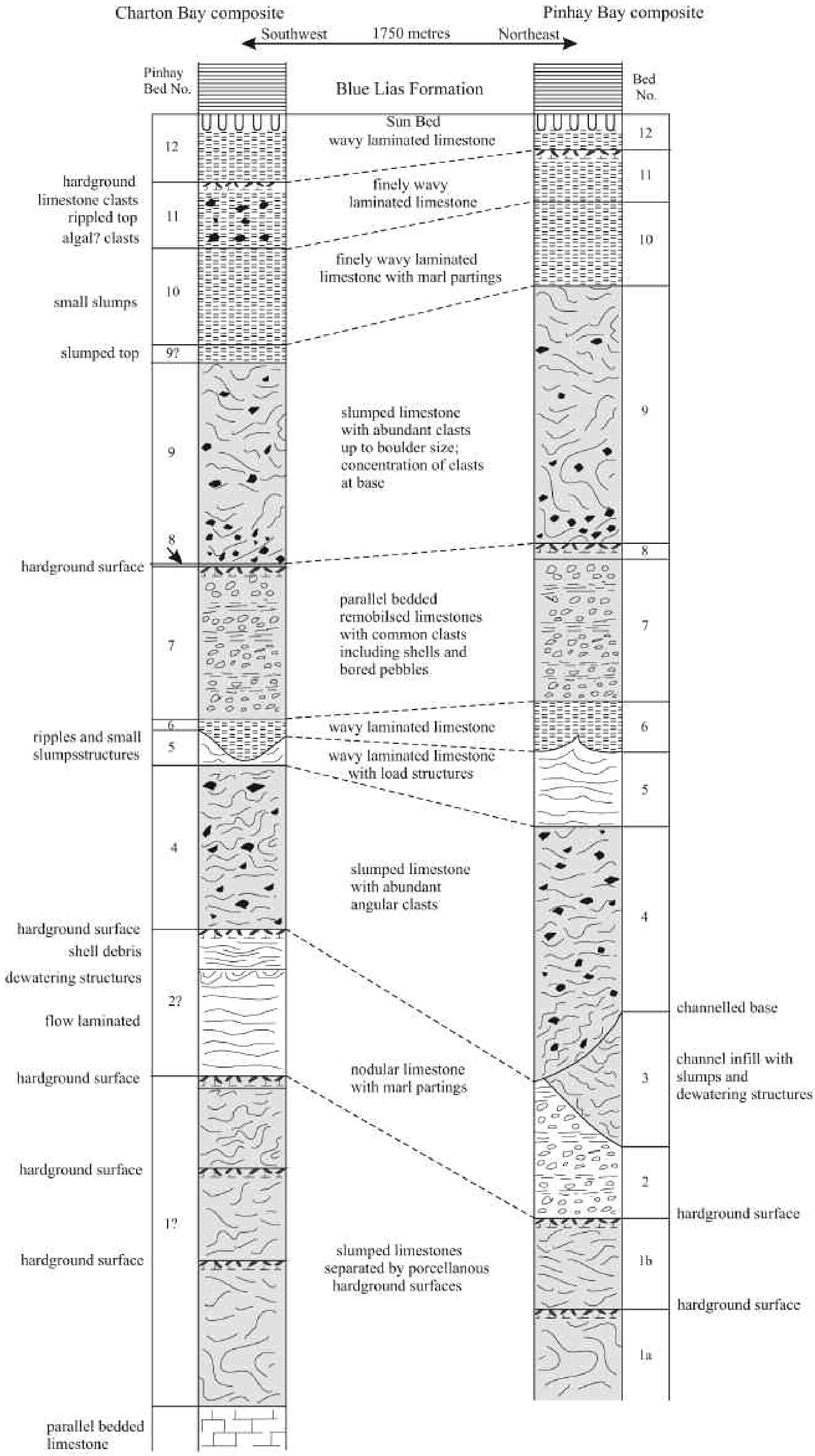

Figure 6. *Correlation of the White Lias successions exposed at Charton Bay and Pinhay Bay.*

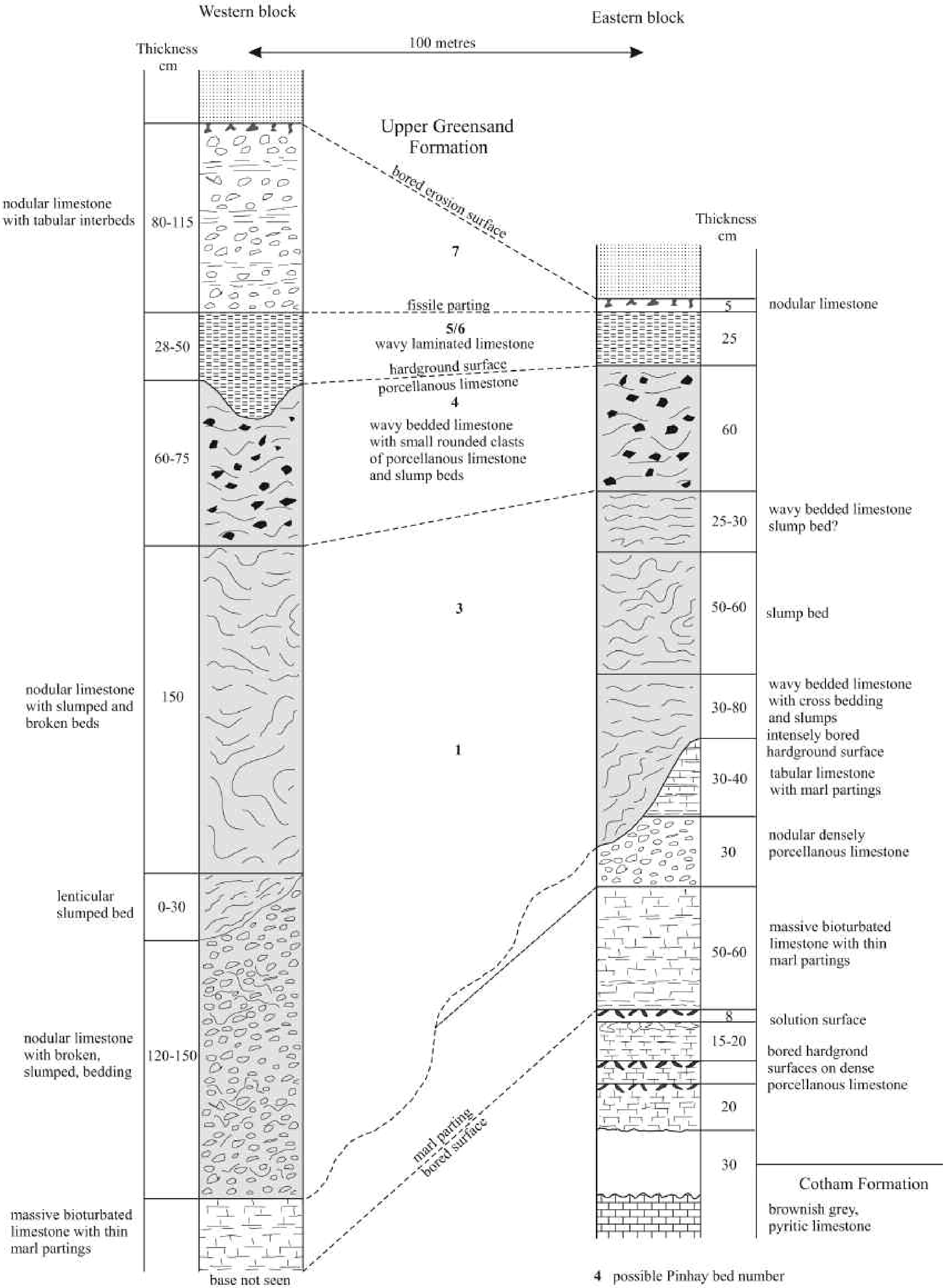

Figure 7. *Lateral variations in the White Lias at Culverhole due to slumping and channelling.*

Figure 8. *White Lias adjacent to Culverhole Foreshore: detail of channel with associated slump.*

sedimentary structures in the lower part of the White Lias is that at Culverhole where rapid lateral variations due to a combination of channelling and slumping can be seen in a series of sections over an outcrop distance of 10 m (Figure 7). Slump structures (Figures 4E, F) and the unconformable junction with the Cretaceous Upper Greensand are especially well displayed.

Hallam (1968) recognised two faunal groups, the benthic fauna described above and a trace-fossil assemblage of burrows and borings. He compared the depositional environments to those of the shallow, warm–water marine lagoons of parts of the present-day Bahamas. Some of Hallam's interpretations of the depositional environments of the White Lias at Pinhay, in particular those relating to emergence, have been challenged by Hesselbo *et al.* (2004) who interpreted the slumped beds as submarine debris flows. In their response to this suggestion, Hallam and Wignall (2004) quoted as evidence of emergence the lithified and brecciated dense porcellanous limestones that occur as angular fragments up to cobble size in the slumped beds.

The simplest explanation of the complex sedimentary structures in the White Lias exposed on the Devon coast is that the limestones were deposited in an area with a large tidal range. This would have given rise at low tides to exposed pavements that were subject to lithification and subsequent brecciation by storm waves, and to networks of drainage channels with slumped margins. Slumped beds were not recorded in the White Lias in former exposures at Uplyme [SY 327 924] and Weycroft, Axminster [ST 311 005], 2 and 10 km north of the coastal exposures respectively. This might indicate that the coastline at that time lay a short distance south of the present-day coast.

The White Lias is capped by an erosion surface throughout southern England marked, at almost all localities, by the characteristic *Diplocraterion* borings of the Sun Bed). At Pinhay Bay this bed is locally absent and is replaced by scour hollows infilled with brecciated limestone (Wignall, 2001; Hesselbo *et al.*, 2004).

Summary and conclusions

In south-west England, the Penarth Group can be divided into three lithologically distinctive units that are here proposed as formations, the Westbury Formation, Cotham Formation and White Lias Formation. The two younger formations are especially well exposed on the east Devon coast.

There has been much debate in recent years as to how to define the Triassic-Jurassic boundary and where to put the Global Boundary Stratotype Section and Point (GSSP). The base of the Jurassic system has traditionally been based on ammonite assemblages, but these are absent or rare in most late Triassic deposits and occur in distinct faunal provinces in the earliest Jurassic prior to the establishment of widespread shelf seas. In NW Europe, including the UK, the long-standing definition has been based on the incoming of smooth-shelled psiloceratid ammonites. In south-west England this places the boundary within a marine sequence a few metres above the erosion surface at the base of the Blue Lias (Cope *et al.*, 1980; Page, 2002). Suggested locations for an ammonite-based GSSP include St Audries Bay, Somerset (Warrington *et al.*, 1994), New York Canyon, Nevada (Guex *et al.*, 2006) and many others, all of which contain either breaks in sedimentation or sections devoid of ammonites. The recent description of an apparently unbroken succession of ammonite assemblages across the late Triassic and early Jurassic in the Tibetan part of the Tethyan Faunal Province (Yin *et al.*, 2007) suggests that further research is required before a type section can be chosen.

Alternative suggestions for defining the base of the Jurassic are based on methods that would enable the boundary to be identified in terrestrial and marine sediments. The most promising of these are a carbon isotope excursion that could be linked to a worldwide event such as an increase in volcanic activity (Hesselbo *et al.*, 2002), and magnetostratigraphy (Hounslow *et al.*, 2004). In the UK, the carbon-isotope event would put the base of the Jurassic in the Cotham Formation (Hesselbo *et al.*, 2004). At the present time the ammonite assemblages remain the most practicable method of defining the boundary in most parts of the World. Whichever method is chosen, the condensed and incomplete nature of the latest Triassic to earliest Jurassic succession in all the outcrops in the UK make them unsuitable for GSSP status.

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