

THE LITHOSTRATIGRAPHY OF THE PENARTH GROUP (LATE TRIASSIC) OF THE SEVERN ESTUARY AREA

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The name Penarth Group was introduced by the Triassic Working Group of the Geological Society to describe a laterally variable succession of brackish and fully marine sedimentary rocks that form a transition from the terrestrial, red-bed facies of the Triassic Mercia Mudstone Group to the fully marine conditions of the Jurassic Lias Group. The Penarth Group is well exposed in cliff and foreshore outcrops near Penarth, South Glamorgan, on the Somerset coast between Blue Anchor and Lilstock, and on the upper reaches of the Severn Estuary at Aust Cliff and Westbury-on-Severn. The group includes strata formerly known as the Westbury Beds, Cotham Beds, Langport Beds, Watchet Beds and White Lias. The current nomenclature is in a confused state. The Westbury Beds were renamed the Westbury Formation by the working group, and the Cotham Beds and White Lias were grouped together to form the Lilstock Formation, in which the renamed Cotham Member is overlain by the Langport Member. In the Severn Estuary area, the Langport Member comprises calcareous mudstones (former Watchet Beds), but throughout much of its outcrop and subcrop it comprises limestones (former White Lias). A revision of the lithostratigraphical nomenclature is proposed in which the name Lilstock Formation is abandoned and the Cotham Formation, Watchet Mudstone and White Lias are defined as lithologically distinct formations that can be recognised throughout southern Britain. The Penarth Group is an attenuated succession that was deposited in shallow-water brackish to marine environments. Each of the formations proposed here is bounded by erosion surfaces, and each contains numerous sedimentary breaks. This needs to be taken into account in any discussion of possible global events, such as sea-level changes, mass extinctions and bolide impacts, close to the Triassic-Jurassic boundary.

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INTRODUCTION

The Penarth Group was defined by the Triassic Working Group as the 'argillaceous, calcareous and locally arenaceous formations of predominantly marine origin which occur between the Mercia Mudstone Group and the base of the Lias' (Warrington *et al.*, 1980). It encompassed the Westbury Beds, Cotham Beds and White Lias of British Geological Survey maps that had, prior to 1980, been collectively referred to as Rhaetic Beds (Table 1). The working group divided the Penarth Group into two formations, the Westbury Formation and the overlying Lilstock Formation named after a locality on the north Somerset coast. The latter was divided into two members, the Cotham Member overlain by the Langport Member, a name derived from Richardson's (1911) division of the White Lias of William Smith (1797) into a limestone facies ('White Lias proper' which he called Langport Beds) and a mudstone facies ('marly beds of the White Lias' which he called Watchet Beds). The limestone facies is represented by a single thin (0.2 to 0.4 m thick) bed of laminated porcellanous limestone at Lilstock Bay and elsewhere on the Severn Estuary coast.

The sections at Penarth Head, St Mary's Well Bay and near Lavernock Point on the South Glamorgan coast (Figures 1 and 2) were defined as the composite type section for the Westbury Formation and the Lilstock Formation and its constituent members (Warrington *et al.*, 1980). These sections are separated by outcrops of younger and older strata over a distance of 5 km of coastline. It is not surprising, therefore, given the shallow-water nature of the sediments, that the succession at all three localities differs in detail. In addition, 'representative sections' of the Lilstock Formation were stated to be present at the

'eponymous locality [ST 177 454]' (Warrington *et al.*, 1980) on the opposite side of the estuary on the Somerset coast. This grid reference defines a 100 m square on the Blue Lias outcrop in the intertidal area in Lilstock Bay. In the absence of nominated type sections accompanied by descriptions that include the definitions of their boundaries, the Penarth Group, Lilstock Formation and Langport Member require revision.

The situation was subsequently partly rectified by the publication of descriptions of the Penarth Group sections of the South Glamorgan and Somerset coasts in Geological Survey memoirs. These descriptions did not, however, clarify the Triassic Working Group nomenclature, but simply highlighted the problem of applying it to the successions exposed in the Severn Estuary area. In the Penarth area, Waters and Lawrence (1987) described the bulk of the Langport Member as the 'Watchet Beds' facies, and at Watchet, Whittaker and Green (1983) divided the Langport Member into 'Langport beds' limestones overlain by 'marly beds'.

The aims of this paper are to describe and correlate the Penarth Group successions exposed in the Severn Estuary area and the adjacent regions, and to use the results to propose a lithostratigraphical nomenclature that is applicable to the whole of the UK outcrop and subcrop. At the base of the group the Westbury Formation is lithologically relatively uniform throughout its onshore outcrop. The basal boundary has been well defined since the 19th Century, and there are detailed published descriptions of the succession at numerous outcrops between Devon and Yorkshire. The present account concentrates, therefore, on the lithostratigraphy of the Cotham Beds, White Lias and Watchet Beds and their replacement, the Lilstock Formation.

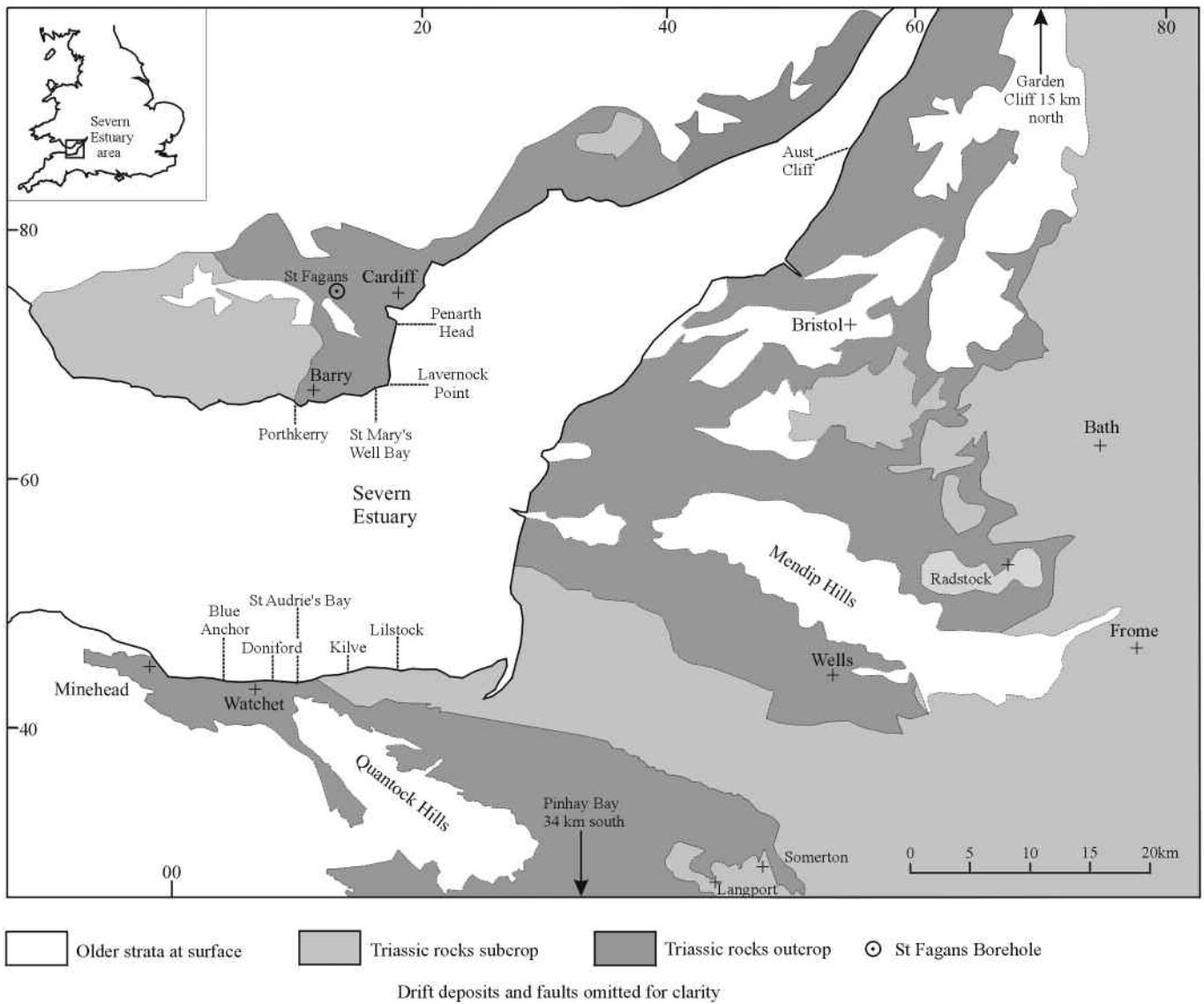


Figure 1. Distribution of the Triassic rocks of the Severn Estuary area showing the positions of the principal outcrops and localities referred to in the text.

Wm Smith, 1797	Richardson, 1911	BGS maps pre-1980	Warrington <i>et al.</i> , 1980	This paper
Blue Lias	Blue Lias	Blue Lias	Blue Lias Fm	Blue Lias Fm
White Lias	White Lias — Watchet Beds — Langport Beds	Rhaetic Beds — White Lias — Cotham Beds — Westbury Beds	Penarth Group — Lilstock Fm — Cotham Mbr — Westbury Fm	Watchet Mudstone Fm
				White Lias Fm
Indigo and Black Marls	Cotham Beds			Cotham Fm
	<i>A. contorta</i> Shales			Westbury Mudstone Fm
Red Ground	Keuper Marl	Keuper Marl	Blue Anchor Fm	Blue Anchor Fm

Fm...Formation Mbr...Member

Table 1. Evolution of the nomenclature of the Penarth Group.

PROPOSED REVISED NOMENCLATURE

In an account of the late Triassic succession on the Devon coast and its correlatives in inland Somerset and the Bath-Bristol area, Gallois (2007) suggested that the Penarth Group should be divided into three formations, in ascending order the Westbury Formation, Cotham Formation and White Lias Formation. All three formations are lithologically distinctive, and are separated by erosion surfaces. Those at the bases of the Westbury and Cotham formations are commonly overlain by pebbly and/or shelly lag deposits rich in vertebrate remains ('bone beds'). Comparison of the Devon and inland successions with those exposed on the Severn Estuary coast in Somerset and South Glamorgan has shown that the Westbury and Cotham formations remain lithologically relatively unchanged, but that the limestones of the White Lias Formation either pass laterally into, or are much reduced in thickness, and are overlain by calcareous mudstones. These last, the Watchet Beds of Richardson (1911), are described here under the proposed new name Watchet Mudstone Formation. The proposed type sections and a selection of reference sections are shown in Table 2.

Westbury Mudstone Formation

The Westbury Beds of Wright (1860), named after the section in the eroding river cliff at Garden Cliff, Westbury-on-Severn (Gloucestershire), were renamed the Westbury Formation by Warrington *et al.* (1980) with a type area at 'Penarth and immediately north of Lavernock Point'. The formation continues to be fully exposed at the original type section at Garden Cliff, but is now less well exposed at Lavernock Point due to sea-defence works and is difficult to access at Penarth (Figure 2a). The formation crops out discontinuously between the Devon coast near Lyme Regis and the North Yorkshire coast near Redcar, and it has an extensive subcrop in the adjacent onshore and offshore areas. In most outcrop areas it comprises 4 to 10 m of dark grey laminated pyritic mudstones that weather to an almost black clay with, locally, subordinate beds of muddy limestone, veins of fibrous calcite ('beef'), shelly limestone and/or fine-grained sandstone. The mudstones maintain their distinctive lithological character over the whole of its outcrop. The modified name Westbury Mudstone Formation is therefore proposed here to reflect this lithological continuity.

Garden Cliff, Westbury-on-Severn is proposed as the type section for historical reasons. There are detailed published descriptions of the full thickness of the formation exposed at all the principal exposures in the Severn Estuary area including those at Westbury Garden Cliff (Richardson, 1904; Benton *et al.*, 2002), in the Penarth area (Richardson, 1905; Waters and Lawrence, 1987) and on the Somerset coast (Richardson, 1911; Whitaker and Green, 1983; Edwards, 1999).

In south-west Britain the formation rests non-sequentially on strata that range in age from Carboniferous to late Triassic (Wilson *et al.*, 1990). At the type section and elsewhere in the Severn Estuary area, the base of the formation is taken at an erosion surface that separates green and grey thinly and thickly bedded silty mudstones and siltstones at the top of the Blue Anchor Formation from overlying laminated dark grey pyritic mudstones (Warrington *et al.*, 1980). At most localities the basal bed of the Westbury Mudstone comprises a pebbly or shelly basal lag deposit rich in fish debris and other vertebrate remains (the 'Rhaetic Bone Bed' of Boyd Dawkins, 1864 and others). The thickest succession recorded in the Severn Estuary is that at Blue Anchor where Richardson (1911) described 14.1 m of Westbury Mudstone.

Cotham Formation

The name Cotham Beds was introduced by Richardson (1911) for 'pale marls and limestones' that rest disconformably and with marked lithological contrast on the Westbury Mudstone on the Somerset coast and in railway cuttings in the Somerton area of Somerset. The name comes from Cotham House, Bristol [ST 5836 7393] where the ornamental Cotham

Marble had been worked at the top of a 3.0 to 3.5 m thick succession of greenish grey calcareous mudstone with thin beds of muddy limestone and ripple-marked sandstone (Kellaway and Welch, 1993). The Cotham Formation is no longer well exposed in the type area, but it remains wholly exposed in the cliffs and foreshores at numerous localities in the Severn Estuary area (Table 2). It has also been wholly exposed from time to time at Culverhole on the Devon coast and, less commonly, at nearby Pinhay Bay. Inland, the mudstones rapidly weather to clay and natural exposures are rare. The full thickness has been exposed in excavations in Avon and Somerset, mostly in road and railway cuttings (Rendle Short, 1904; Richardson, 1911).

In the absence of a suitable type section in the Cotham area, St Audrie's Bay, Somerset is proposed as the replacement. This is an extensive exposure [ST 0989 4370 to 1017 4339] on a wave-cut platform that includes all the principal lithological and sedimentary features that characterise the formation in the Severn Estuary area. The published descriptions of the formation exposed in the Severn Estuary area are the same as those for the Westbury Mudstone. All of these placed the base of the formation at an erosion surface that marks an upward lithological change from dark grey mudstones to greenish grey mudstones. At all the localities examined in the present survey the base of the Cotham Formation is marked by a gently undulating erosion surface, with or without a thin (mostly <30 mm thick) pyrite-cemented shelly or coarse sandy lag deposit with common fish teeth (Figure 2c and 2f).

In most areas the formation comprises 2 to 4 m of greyish green mudstone with thin interbeds of limestone and sandstone that were deposited in shallow and very shallow brackish-water and restricted-marine environments. The proportion and composition of the non-mudstone component varies from area to area. In the Severn Estuary area, the formation can be divided into two parts separated by a prominent desiccated erosion surface (D in Figures 3, 5 and 6). The lower part, here named the Lower Cotham Member, comprises lenticular-bedded greenish grey mudstones and siltstones with dewatering structures, and slump structures that locally involve all or part of the beds below the erosion surface. The slumped beds are laterally impersistent over distances of tens to hundreds of metres, are not all at the same stratigraphical level with respect to the base and top of the member, and are not present at every locality (Figures 3 and 5). On the Glamorgan coast the whole of the Lower Cotham Member and the top part of the Westbury Mudstone is disturbed by slump and dewatering structures. At St Mary's Well Bay, 1.3 km SW, the same beds are undisturbed (Figures 2b and 2c). Similarly, at Lilstock, disturbed beds in the upper part of the Lower Cotham Member pass laterally into undisturbed beds over a distance of 100 m.

At the base of the Upper Cotham Member, sheets of ripples of quartz and shell-debris sand, and limestone ooids form a widespread marker bed in the Severn Estuary area (Figures 2d, 3 and 4c), and the same lithologies infill desiccation cracks (Figures 2c and 4b) (Waters and Lawrence, 1987; Wilson *et al.*, 1990). Rippled calcareous sandstones and calcarenites are present at one or more different levels in the Cotham Formation in the Bath-Bristol, inland Somerset and Devon areas. In the absence of palaeontological evidence, it is not known if these were deposited contemporaneously. At Culverhole, Devon, the most prominent sandstone bed and desiccation surface lies at the base of the formation (Gallois, 2007).

The upper part of the Cotham Formation in the Severn Estuary area contains laterally variable amounts of tabular bedded and nodular muddy limestone and porcellanous limestone within a predominantly mudstone succession. One of the limestone beds is locally lithologically similar to parts of the White Lias, with the result that different authors have placed the upper boundary of the Cotham Formation at different stratigraphical levels. Richardson's (1911) identification of the upper boundary of his Cotham Beds relied on the recognition of the Cotham Marble, small dome-shaped masses of algal-stromatolite limestone mostly <0.2 m thick. This bed has

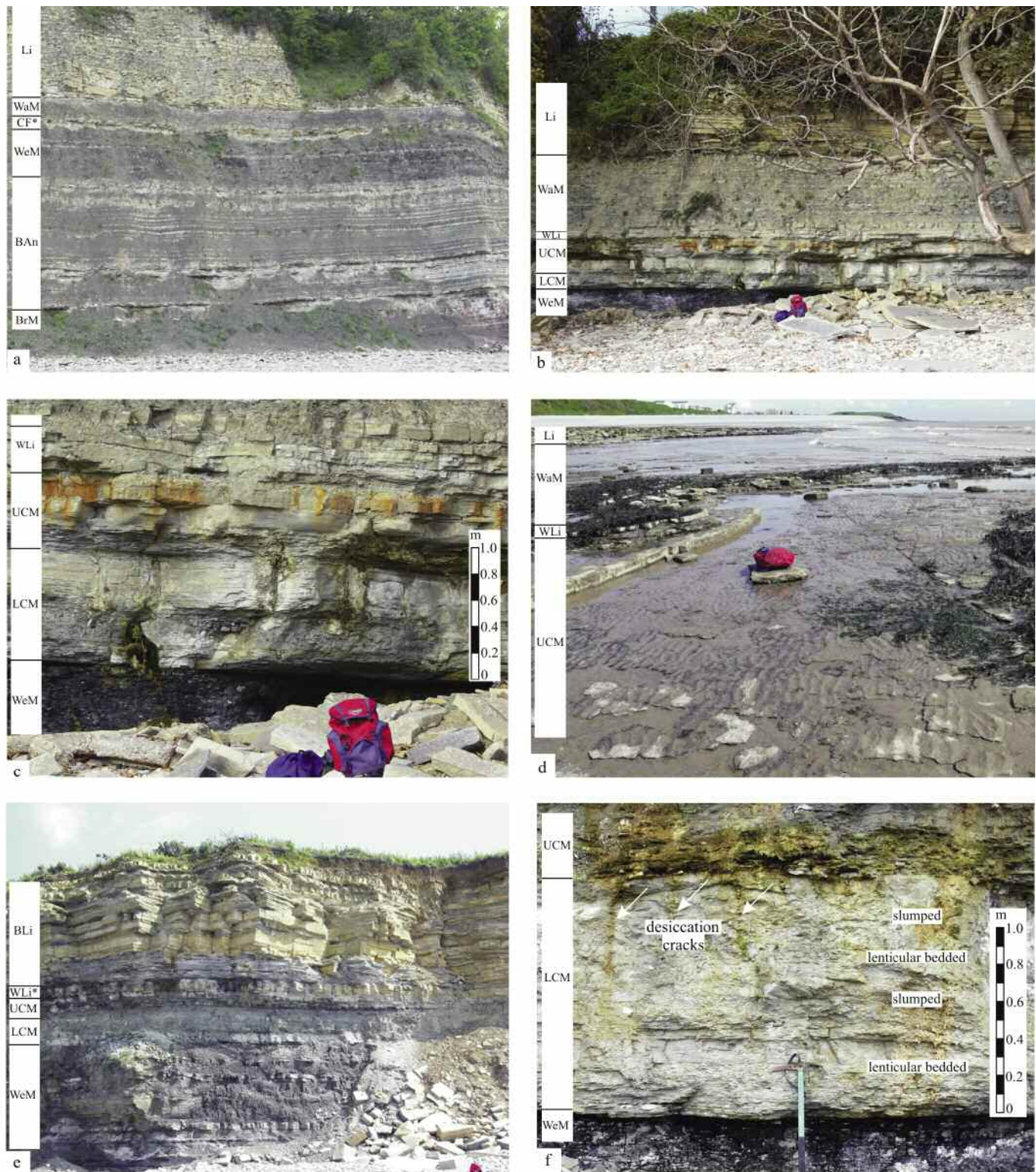


Figure 2. Examples of Penarth Group lithologies in the Severn Estuary area. **(a)** The Penarth Group succession at Penarth Head, South Glamorgan. The cliff is about 30 m high: see Figure 3 for measured section. Photograph partially rectified for parallax. **(b)** The Penarth Group succession at St Mary's Well Bay, South Glamorgan. The cliff is about 7.5 m high: see Figure 3 for measured section. **(c)** Detail of the lower part of the succession shown in (b). Lenticular bedded greenish grey Lower Cotham Formation mudstones and siltstones rest with sharp lithological contrast on an irregular surface cut into dark grey Westbury Mudstone. A lag deposit with shell and fish debris infills many of the hollows. **(d)** Ripples of ooids, shell debris and sand at the base of the Upper Cotham Member overlain by a thin bed of porcellanous limestone (White Lias) and calcareous mudstones (Watchet Mudstone) exposed in the intertidal area at Portbkerry, South Glamorgan. View east towards Barry Island and town. **(e)** The Penarth Group succession at Lilstock Bay, Somerset. The cliff is about 20 m high: see Figure 5 for measured section. Photograph uncorrected for parallax. **(f)** Lower Cotham Member at Lilstock Bay, Somerset showing irregular contact with the Westbury Mudstone overlain by lenticular bedded greenish grey siltstones and mudstones with laterally impersistent slumped beds at two horizons. The base of the sandy Upper Cotham Member is marked by a desiccation surface. Abbreviations: BrM - Branscombe Mudstone Formation, BAn - Blue Anchor Formation, WeM - Westbury Mudstone Formation, CF - Cotham Formation (LCM - Lower Cotham Member; UCM - Upper Cotham Member), WLi - White Lias Formation, WaM - Watchet Mudstone Formation, Li - Lias Group, CF* includes thin WLi in (a), WLi* includes thin WaM in (d).

Formation	Type Section	Selected Reference Sections	National Grid Reference
Blue Lias	Pinhay Bay, Devon* [SY3220 9085]	Lilstock Bay, Somerset	ST 1779 4535*
		St Audrie's Bay, Somerset	ST 1015 4350*
		Lavernock Point, South Glamorgan	ST 1870 6814*
		St Mary's Well Bay, South Glamorgan	ST 1745 6779*
		Porthkerry Bay, South Glamorgan	ST 0903 6674*
Watchet Mudstone	Doniford Bay, Somerset [ST 0830 4350]	Lilstock Bay, Somerset	ST 1779 4535
		St Audrie's Bay, Somerset	ST 1015 4350
		Blue Anchor, Somerset	ST 0387 4387
		Lavernock Point, South Glamorgan	ST 1870 6814
		St Mary's Well Bay, South Glamorgan	ST 1745 6779
White Lias	Pinhay Bay, Devon [SY3177 9080]	Bowden Lane, Langport, Somerset	ST 4157 2653
		New Cut, Wells, Somerset	ST 5493 4727
		Charton Bay, Devon	SY 3004 9005
		Culverhole, Devon	SY 2720 8943
Cotham	St Audrie's Bay, Somerset [ST 1015 4350]	Aust Cliff, Avon	ST 5690 8995
		Lilstock Bay, Somerset	ST 1779 4535
		Doniford Bay, Somerset	ST 0830 4350
		Blue Anchor, Somerset	ST 0387 4387
		Lavernock Point, South Glamorgan	ST 1870 6814
		St Mary's Well Bay, South Glamorgan	ST 1745 6779
		Porthkerry Bay, South Glamorgan	ST 0903 6674
		Culverhole, Devon	SY 2720 8943
Westbury Mudstone	Garden Cliff, Westbury-on-Severn Glos. [SO 7184 1280]	Aust Cliff, Avon	ST 5690 8995
		Lilstock Bay, Somerset	ST 1779 4535
		Doniford Bay, Somerset	ST 0830 4350
		Blue Anchor, Somerset	ST 0387 4387
		Penarth Head, South Glamorgan	ST 1914 7196
		Lavernock Point, South Glamorgan	ST 1870 6814
		St Mary's Well Bay, South Glamorgan	ST 1745 6779

* grid reference refers to location of basal beds: higher parts of the formation are exposed in adjacent sections

Table 2. Proposed type and reference sections for the Penarth Group formations.

a widespread distribution in the eastern part of the outcrop between Bath and the east Devon coast, but the distribution is patchy on both local and regional scales. Cotham Marble is well developed at Aust Cliff, but has not been recognised in the sections south of there on the Somerset and Glamorgan coasts. Bristow and Etheridge (1873) recorded an 'equivalent of the Cotham Marble' at St Audrie's Bay and Richardson (1911) identified a 'position of Cotham Marble' there, but at a different stratigraphical level. In practice the phrase 'equivalent of the Cotham Marble' has little meaning: the distinctive stromatolitic limestone is either present in any given section or it is not.

The use of this bed as a stratigraphical marker is further complicated by the presence in many inland sections of 'false Cotham Marble', a stromatolitic limestone that occurs at a lower stratigraphical level, and 'Crazy Cotham', a limestone breccia with angular clasts of stromatolitic limestone that can occur at the top of, and within, the upper part of the Cotham Formation. In the present work the top of the formation has been taken at an erosion surface at the top of a prominently bioturbated

limestone hardground. This marks a sharp upward change to a porcellanous limestone that is lithologically similar to parts of the White Lias Formation.

White Lias Formation

The names White Lias and Blue Lias, adopted from quarrymen's terms that had probably been in use in Somerset for several hundred years, were first used in a formal geological sense by William Smith in an unpublished Table of Strata (1797) that accompanied a geological map of the area around Bath (Arkell, 1933). According to Arkell and Tomkeieff (1953) the word *lias* was adopted from the Old French word *liois*, meaning a compact type of limestone. The name White Lias remained in geological use until 1980 when it was abandoned by the Triassic Working Group. Blue Lias was retained by the Jurassic Working Group (Cope *et al.*, 1980), who followed the recommendation in international stratigraphical codes that the stability of nomenclature should be maintained by the use of

the rule of priority and by the preservation of well-established names. White Lias and Blue Lias, together with Fuller's Earth and Forest Marble from the same William Smith table, are the oldest formal geological names in Britain. Limestones of the sort that characterise the White Lias of the Bath area crop out discontinuously between the east Devon coast and Nottinghamshire (Donovan *et al.*, 1979; Swift, 1995).

In the absence of a suitable permanent section in the Bath type area, the sea cliff at Pinhay Bay, Devon [SY 3177 9080 to 3220 9085], which Hallam (1960) described as 'incomparably the best section in the country', is proposed as the type section. The combined sections at Pinhay Bay and those at Charton Bay and Culverhole expose up to 9 m of fine-grained limestone with thin (<50 mm thick) mudstone partings. At Bath, the base of the formation was taken at the top of the 'Cotham Stone' (=Cotham Marble) by William Smith (1797). In Devon (Gallois,

2007) and inland Somerset (Richardson, 1911), the junction with the Cotham Formation appears to be everywhere marked by an irregular erosion surface, with or without Cotham Marble. In the Severn Estuary area, where the bulk of the limestone passes laterally into calcareous mudstone, the White Lias is represented by a single thin bed (mostly 0.2 to 0.4 m thick) of porcellanous limestone.

The White Lias exposed on the Devon coast contains channels, slumps and fractured hardground surfaces that are atypical of the formation as a whole (Gallois, 2007). In the Bath area, Donovan and Kellaway (1984) divided the White Lias into a lower part characterised by rubbly limestones with thin beds of mudstone and an upper part with more evenly bedded limestones with thin (<50 mm thick) mudstone partings (Figure 4d). Almost all published accounts of exposures of White Lias in southern England describe the top of the

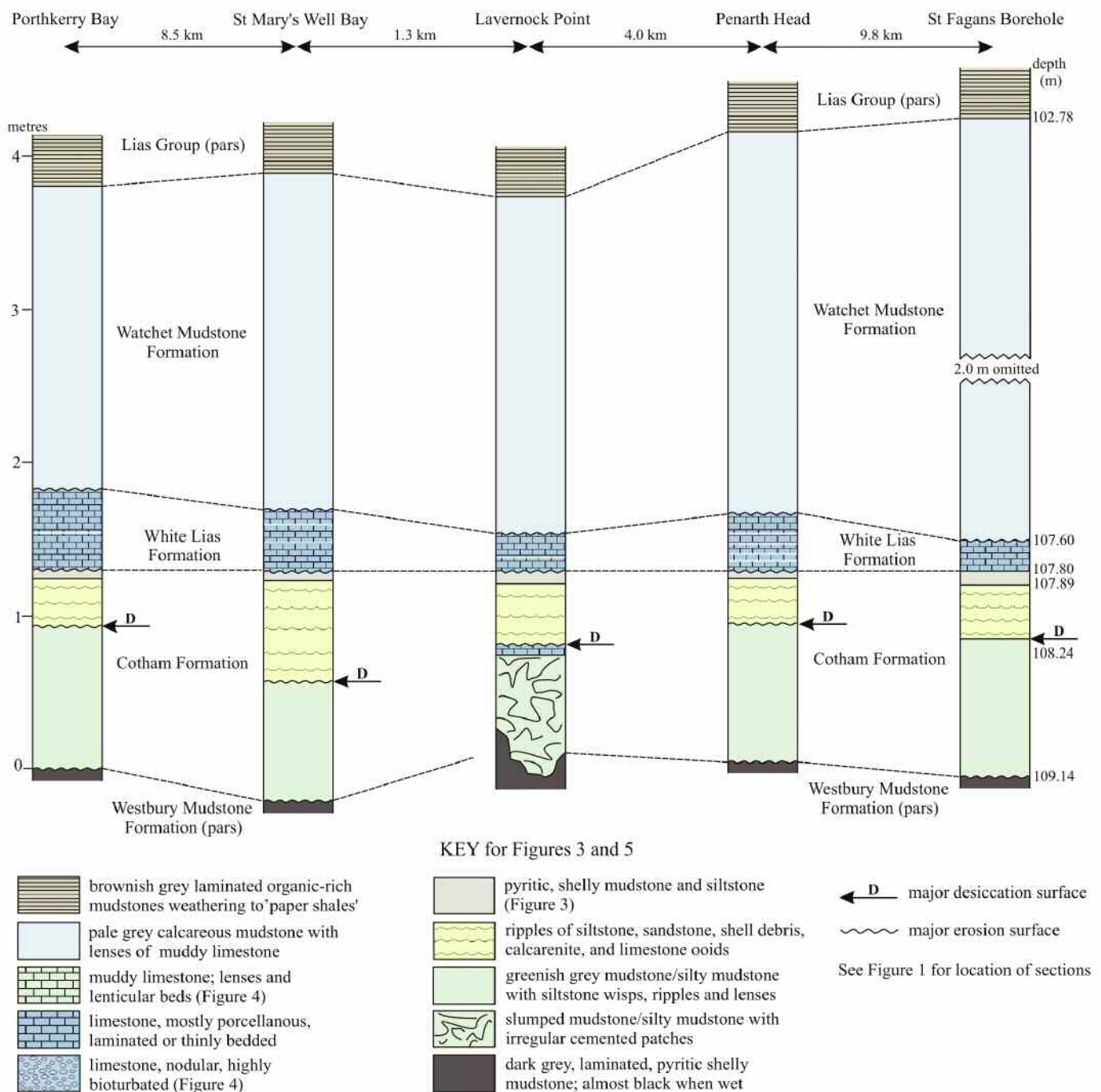


Figure 3. Correlation of the Cotham Formation, White Lias Formation and Watchet Mudstone Formation successions exposed in the cliff and foreshore sections in the Penarth area, South Glamorgan.

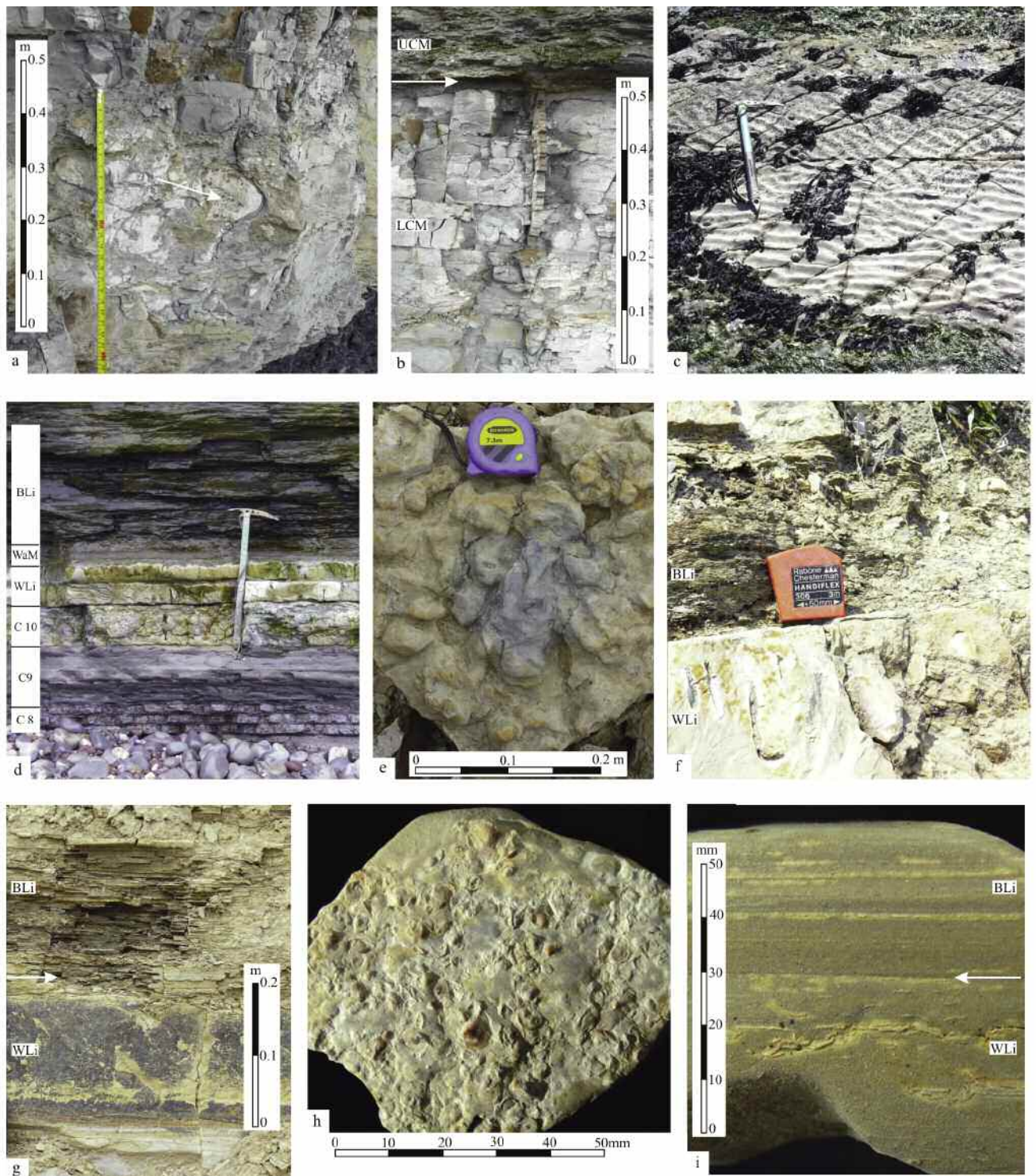


Figure 4. Examples of Penarth Group lithologies in Somerset and Devon. (a) Slumped mudstones and siltstones in the Lower Cotham Member, Lilstock Bay. Arrow indicates axis of NW plunging fold. (b) Sand-filled crack descending from the desiccation surface at the base of the Upper Cotham Member, Lilstock Bay, Somerset. (c) Layers of symmetrical wave ripples separated by desiccation surfaces. Basal bed (C5) of the Upper Cotham Member, Doniford Bay, Somerset. (d) Junction of the Penarth Group and Lias Group at Lilstock Bay, Somerset. The highest bed of the Cotham Formation (C10) is a highly bioturbated limestone with abundant *Thalassinoides* burrows that is capped by a mineralised hardground surface. The White Lias is represented by a single bed of porcellanous limestone throughout the Somerset and South Glamorgan coastal sections. The Watchet Mudstone at Lilstock Bay is a bioturbated, shelly calcareous mudstone with laterally variable beds of muddy limestone. The junction with the overlying Blue Lias is conformable. (e) View from above of the penecontemporaneously solution affected top surface of a porcellanous limestone close above the base of the White Lias, Bowden Land Quarry, Langport, Somerset. (f) Porcellanous, White Lias limestone (Sun Bed auct.) unconformably overlain by fissile weathering, laminated organic-rich mudstones (paper shales) at the base of the Blue Lias. Numerous *Diplocraterion* burrows descend from the unconformity surface. Charton Bay, Devon. (g) Weathered White Lias-Blue Lias junction, Bowden Lane Quarry, Langport, Somerset. The highest limestone bed of the White Lias is overlain by up to 40 mm of bioturbated, shelly calcareous mudstone that is lithologically similar to that of the Watchet Mudstone. This bed is conformably overlain by laminated organic-rich mudstones at the base of the Blue Lias. (h) Concentration of small bivalves on the top surface of the White Lias at the exposure shown in (g). (i) Detail of the White Lias-Blue Lias boundary shown in (g). Abbreviations: as Figure 2; C9 numbered bed in Cotham Formation. Ice axe in (c) and (d) is 0.75 m long.

formation as a desiccated erosion surface from which characteristic *Diplocraterion* borings descend (the Sun Bed *aucti*). This is overlain with marked lithological contrast by fissile-weathering, laminated organic-rich mudstones (paper shales of early authors) at the base of the Lias Group (Figure 4f). The sedimentary break at the base of the Lias is locally more prominent and represented by scour hollows infilled with mudstones with limestone clasts (e.g. Donovan and Kellaway, 1984, figure 13; Hesselbo *et al.*, 2004, figure 10). In the Severn Estuary area, the White Lias is represented by a single thin bed (0.2 to 0.4 m thick) of limestone capped by an irregular hardground surface (Figure 4e). In inland Somerset, in the Langport area, White Lias limestone is locally overlain by a thin bed of bioturbated shelly mudstone (Figures g, h, i).

Watchet Mudstone Formation

Richardson (1911) introduced the name Watchet Beds to describe 'marls with inconspicuous and impure limestone layers' that have a restricted outcrop in the Severn Estuary area. He noted that the marls were distinct from the limestones of the White Lias and that they decreased in thickness eastwards as the limestones increased in thickness in the same direction. However, at some localities (notably Lilstock Bay) Richardson (1911) included part of the overlying laminated organic-rich mudstones in the Watchet Beds. This led Whittaker (1978) to conclude that the 'greater part' of the Watchet Beds exposed on the Somerset coast were the basal bed of the Lower Lias. He subsequently (in Whitaker and Green, 1983, figure 12) classified the remaining part of the Watchet Beds as the 'marly' upper part of the Langport Member of Warrington *et al.* (1980). The beds for which the name Watchet Mudstone Formation is proposed here are lithologically distinct from the White Lias and from the laminated organic-rich mudstones of the basal Lias. The formation is thicker on the South Glamorgan coast than on the Somerset coast, but the name Watchet is retained for continuity with a proposed type section at Doniford Bay, Watchet.

Richardson (1911) described Watchet Beds overlain by Lower Lias mudstones at Lilstock Bay, St Audrie's Bay and Blue Anchor, and Whittaker and Green (1983) described similar successions at Lilstock Bay, St Audrie's Bay and Doniford Bay (Helwell Bay of some authors). Richardson (1905) described the stratigraphically equivalent successions at Lavernock Point and St Mary's Well Bay.

The Watchet Mudstone comprises thinly and thickly bedded, pale and medium grey calcareous mudstones and silty mudstones with variable carbonate and shell (mostly bivalve) contents. Lenticular and/or nodular beds of muddy limestone are locally common in the lower part of the formation. At the type section and the reference sections, the base of the formation is taken at an erosion surface at which calcareous mudstone infills an irregular surface at the top of the porcellanous limestone of the White Lias. On the Somerset coast, the formation thickens westwards from 0.15 m at Lilstock Bay (Figure 4e) to about 0.5 m in the Watchet area (Figure 5). The sections at Lilstock Bay show marked lateral variations in lithology over a distance of about 300 m with one or more sedimentary breaks. They include porcellanous limestone, calcareous mudstone and ripple-marked calcareous sandstone and siltstone.

The more westerly successions on the Somerset coast consist of calcareous mudstone with variable amounts of muddy limestone. In South Glamorgan, where the formation is up to 2.2 m thick in the coastal exposures and 4.8 m thick in the St Fagans Borehole [ST 1169 7813] (Waters and Lawrence, 1987), it is composed almost wholly of calcareous mudstone and silty mudstone (Figure 3). The top of the formation in all the sections examined during the present study has been taken at a sharp upward change from pale grey calcareous mudstone to laminated brownish grey organic-rich mudstone with common fish scales. The boundary is planar at all the localities examined. It has been interpreted as a change from an aerobic to a dysaerobic or anaerobic environment (Hesselbo *et al.*,

2004). In sections in the Langport area in Somerset where the Sun Bed is absent, the White Lias is conformably overlain by a thin (<0.3 m thick) equivalent of the Watchet Mudstone which is itself overlain conformably by the Blue Lias.

Blue Lias Formation (Lias Group)

The base of the Lias in south west Britain was taken by Richardson (1905; 1911) and other early authors at the base of laminated, brownish grey organic-rich mudstones that characteristically weather to fissile 'paper shale'. In southern Britain these rest with lithological contrast either conformably on the Watchet Mudstone (this paper) or disconformably on the White Lias (Donovan and Kellaway, 1984). The type section of the Blue Lias at Saltford railway cutting [ST 685 671 to 681 676], near Bath (Cope *et al.*, 1980) is now largely obscured. The continuous cliffs between Pinhay Bay and Monmouth Beach, Lyme Regis, permanently expose the full thickness of a Blue Lias succession that is lithologically similar to that at the Bath type section. It should be considered as a possible replacement type section.

LOCALITIES

Penarth area

The 'Lilstock Formation' successions exposed at the three exposures that comprise the 'composite type section' of Warrington *et al.* (1980) are graphically summarised in Figure 3, together with that proved in the nearby continuously cored St Fagans Borehole. The lithologies and thicknesses recorded here are closely similar to those of Waters and Lawrence (1987), and the stratigraphical interpretation differs only in minor detail.

The most complete exposure of the Cotham and Watchet Mudstone formations on the South Glamorgan coast is that in the cliff at St Mary's Well Bay (Figure 2b) where the section presented in Table 3 was measured.

The exposures in the intertidal areas at Lavernock Point [ST 1867 6816 to 1874 6811] Barry Harbour [ST 1055 6665] and Porthkerry Bay, in the cliff at Penarth Head and in the continuously cored St Fagans Borehole [ST 1169 7813], exhibit a similar succession of lithologies to that exposed in the cliff at St Mary's Well Bay, with one notable exception (Figure 3). At Lavernock Point all or part of the Lower Cotham Member mudstones and siltstones and, locally, the highest part of the Westbury Mudstone are slumped. The thickness of the slumped beds varies from 0.45 to 1.00 m over distances of tens of metres. Angular clasts and lenses of dark grey Westbury Mudstone are common in the lower part of the slumped beds. Where undisturbed, the base of the Cotham Formation is channelled into the Westbury Mudstone. Elsewhere, the boundary is blurred by soft-sediment deformation.

The desiccation surface at the base of the Upper Cotham Member is well exposed on the foreshore at Lavernock Point where infilled cracks up to 0.08 m wide, some of which descend down into the Westbury Mudstone, form polygons up to 0.90 m across (Waters and Lawrence, 1987). The overlying sandstones comprise sheets of mostly symmetrical wave ripples with, at several levels, polygonal desiccation cracks 1 to 2 mm wide that penetrate one or more beds. The sedimentological features are indicative of deposition in a relatively shallow marine or intertidal environment that experienced periods of emergence (Hesselbo *et al.*, 2004). The more westerly exposures of the sandstones contain a greater proportion of limestone ooids than the more easterly localities (e.g. Wilson *et al.*, 1990, plate 14F). The beds above the sandstones are laterally variable in thickness and lithology at each locality and between each of the sections shown in Figure 3. Their sedimentology suggests deposition in shallow sub-tidal environments with one or more sedimentary breaks present in each of the measured sections.

The Cotham Formation exposed in all the sections on the south Glamorgan coast is capped by a calcitised and pyritised

hardground surface that is overlain by a thin representative of the White Lias. This bed of porcellanous limestone thickens westwards from 0.20 m in the St Fagans Borehole to 0.65 m at Porthkerry Bay (Waters and Lawrence, 1987). Its correlative on the Somerset coast is a lithologically identical bed that maintains the same thickness (0.21 to 0.22 m) in all the sections between Lilstock and Blue Anchor.

The Watchet Mudstone Formation at outcrop in the Penarth area comprises 2.2 to 2.5 m of relatively uniform calcareous mudstones and silty mudstones with a variable shell content that ranges from barren to small patches of oyster-rich shell coquina (Figure 3). In the thicker, unweathered succession proved in the St Fagans Borehole, Waters and Lawrence (1987) recorded bioturbation and thin (up to 15 mm thick) beds of cross-bedded fine-grained sandstone, and graded beds of shelly, muddy limestone up to 90 mm thick.

Somerset coast

The full thickness of the Penarth Group is exposed at five principal locations on the Somerset coast (Figure 5), mostly in intertidal areas. In addition, parts of the group are exposed in fault-bounded blocks in the intertidal area between Blue Anchor and Watchet, and at Kilve. The most complete cliff section is that at Lilstock Bay [ST 1779 4535 to 1789 4531] where the base of the Westbury Formation is exposed at times of low storm-beach level, and the remainder of the Penarth Group and the lower part of the Blue Lias Formation are permanently exposed (Figure 2e). The former cliff section at St Audrie's Slip [ST 1070 4330] (Bristow and Etheridge, 1873; Woodward and Ussher in Ussher, 1908; Richardson, 1911) is now overgrown, but the same succession is exposed in the adjacent intertidal area. The sections at Doniford Bay and Blue Anchor expose similar successions, and are often less obscured by seaweed.

Stratigraphic unit and description	Thickness (m)
<i>Lias: St Mary's Well Bay Formation (pars)</i>	
Limestone, bluish grey, argillaceous, tightly cemented	0.09
Mudstone, interlaminated grey and brownish grey, organic-rich, fissile weathering; sharp, planar base	0.32
<i>Watchet Mudstone Formation (2.20 m)</i>	
Mudstone, medium and pale grey, calcareous, mostly thickly bedded with blocky weathering; minor interbeds of darker grey, thinly bedded mudstone and very pale grey harder mudstone with a higher carbonate content; sparsely fossiliferous with concentrations of bivalves, mostly <i>Liostrrea</i> and <i>Modiolus</i> , on a few bedding planes; bioturbated in lower part	2.15
Mudstone, crowded with whole and fragmentary <i>Liostrrea</i> and shell fragments; passes laterally into dense shelly limestone at Lavernock Point; infills irregular top of underlying bed at both localities	0.02 to 0.05
<i>White Lias Formation (0.30 to 0.40 m)</i>	
Limestone, dense, micritic, laminated with porcellanous texture; three beds 0.09 to 0.20 m thick separated by thin (10 to 50 mm thick) beds of calcareous mudstone that infill the irregular upper surfaces of the limestones; laterally variable; 0.20 to 0.30 m thick at Lavernock Point separated into two beds by a single mudstone parting; irregular base with ferruginous seepages	0.30 to 0.40
<i>Cotham Formation (1.50 m)</i>	
<i>Upper Cotham Member</i>	
Sandstone/calcareenite, medium- and coarse-grained; laterally variable complex bed with ripples of pyrite-cemented shell debris in lower and upper parts, and laterally impersistent lenses of porcellanous limestone up to 0.06 m thick in middle part; capped by irregular mineralised hardground surface; irregular base possibly infills a shallow channel	0.18 to 0.20
Sandstone, fine-grained, calcareous, stacked ripples	0.13
Sandstone, fine-grained, calcareous with wavy bedding lamination	0.17
Sandstone, fine-grained, shell debris and siltstone forming stacked ripples with mudstone partings; desiccation surface at base with sandstone-filled cracks up to 30 mm wide and 0.4 m deep	0.23
<i>Lower Cotham Member</i>	
Interlaminated greenish grey mudstone and grey siltstone, weakly calcareously cemented	0.38-0.40
Mudstone, pale greenish grey, silty, weakly calcareous with blocky and sub-conchoidal weathering	0.24
Mudstone, pale greyish green, lenticular-bedded with laminae and lenses of grey siltstone including incipient single ripples of coarse siltstone; sharp planar and gently undulating base overlain by up to 10 mm of pyrite-cemented shell fragments and debris (mostly thin-shelled bivalves) with common fish debris	0.16
<i>Westbury Mudstone Formation (pars)</i>	
Mudstone, dark grey, laminated, pyritic in part; shelly at many levels with common crushed bivalves	0.50 (seen)

Table 3. Stratigraphic section through the Cotham and Watchet Mudstone formations on the South Glamorgan coast at St Mary's Well Bay.

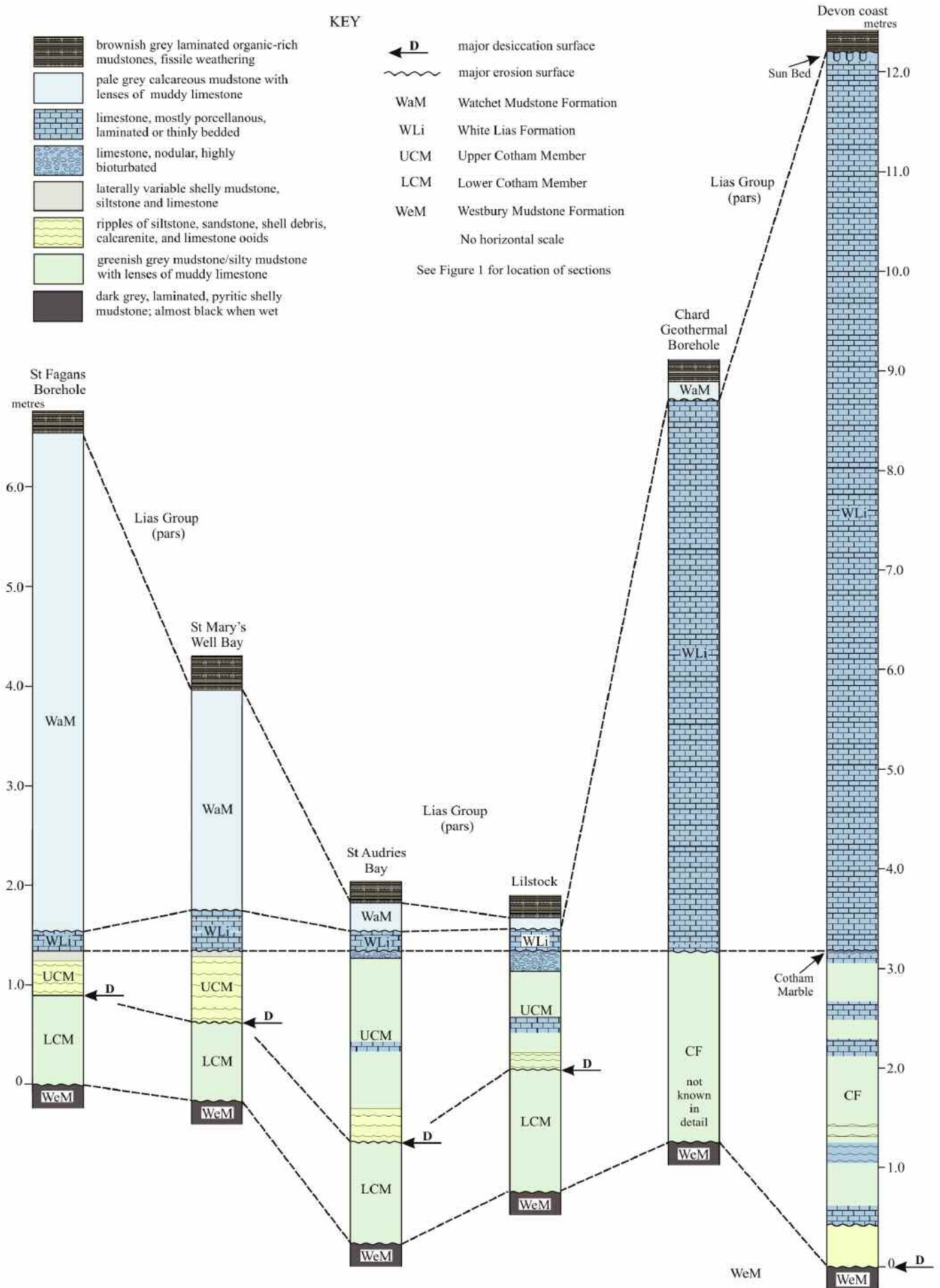


Figure 6. Correlation of the Penarth Group successions exposed on the Devon, Somerset and South Glamorgan coasts (for key see Figure 3).

The succession measured on the wave-cut platform [ST 0989 4370 to 1017 4339] at St Audrie's Bay is presented in Table 4. Cotham Formation bed numbers are those shown in Figure 5.

The Westbury Mudstone, White Lias and basal Blue Lias successions exposed over a distance of about 20 km on the Somerset coast show little lateral variation in lithology, in contrast to those of the Lower Cotham Member and the Watchet Mudstone. At Blue Anchor, Doniford Bay and St Audrie's Bay, the basal bed of the Cotham Formation is a laterally variable and complexly slumped bed with clasts of Westbury Mudstone. The junction between the two formations is sharp, and in most sections is irregular. The basal bed at Kilve Bay and Lilstock Bay is a lenticular-bedded mudstone, similar to that exposed at St Mary's Well Bay, that rests on an irregular erosion surface (Figure 2f) and lag deposit rich in fish debris. The erosion surface at the base of the Upper Cotham Member is present in all the Somerset coast sections where it cuts out progressively more of the underlying beds in a westerly direction (Figure 5). Large-scale desiccation cracks descend from the base of the sandstones (Bed C5) in all the sections examined, and small-scale desiccation polygons are present within the sandstones. The thickness and lithology of this bed shows little variation except at Lilstock Bay where it is represented by two (locally three) laminae of ripples separated by mudstones. The Upper Cotham Member is thicker on the Somerset coast than in the Penarth area (Figures 3 and 5). It comprises greenish grey mudstones with laterally variable amounts of muddy limestone and two prominent limestone marker beds. The older of these (Bed C7) is a thinly bedded porcellanous limestone that weathers into thin slabs. Richardson (1911) called this bed the 'Cotham Marble equivalent' and Whitaker and Green (1983) placed it at the base of the Langport Beds (= White Lias). However, it is overlain in all the Somerset coast sections by mudstones of Cotham Formation lithology. The higher bed (Bed C10) is a highly bioturbated limestone with abundant *Thalassinoides* burrows that is capped by a mineralised hardground surface. This surface is here correlated with a similar surface that is present at the top of the Cotham Formation on the south Glamorgan coast. This is overlain by a bed of porcellanous limestone with mudstone partings (White Lias) as in the Penarth area.

The Watchet Mudstone successions thicken and become more lithologically uniform in a westerly direction on the Somerset coast (Figure 5), but the formation does not reach the thickness exposed on the Welsh coast. The lithologies at St Audrie's Bay to Blue Anchor are similar to those of the Penarth area. That at Lilstock, where it contains a high sand content and two or more erosion surfaces, is markedly more attenuated.

Inland Somerset

The Penarth Group is poorly exposed inland in south-west Britain. The sections in railway cuttings in Somerset described by Richardson (1911), where the group was formerly wholly exposed, are now either backfilled (e.g. Three Arch Bridge, Shepton Mallett [ST 602 429]; Chilcompton Old Down [ST 631 512]) or difficult to access for Health and Safety reasons (e.g. Dunball, Puriton [ST 3135 4120]; Charlton Mackrell [ST 5250 2868] and Sparkford Hill [ST 6062 2662]).

GLOBAL EVENTS AND THE TRIASSIC-JURASSIC BOUNDARY

The change from terrestrial to marine environments that the relatively thin Penarth Group successions represent, their proximity to the Triassic-Jurassic boundary, and the presence of a major world-wide extinction event in the latest Triassic has led to the publication of a wide range of sedimentological, palaeontological and geochemical studies on the Penarth Group. Almost all of these have drawn their conclusions from two sections, St Audrie's Bay and Lavernock Point.

At Lavernock Point, Richardson (1905) recorded granular material from the ripple-marked calcareous sandstones in the Cotham Formation that had filtered down cracks in the underlying greyish green mudstones. He interpreted this as evidence of a 'non-sequence caused by a slight upheaval'. Mayall (1983) noted that the sand-filled cracks and the desiccation surface from which they descended were widespread in the Severn Estuary area, and that at some localities the underlying mudstones contained synsedimentary deformation structures including dewatering features and slumped beds. He suggested that the deformation was caused by earthquake activity and an associated uplift of 1-2 m of the South Glamorgan-north Somerset area. Simms (2004) described the slumped beds as a single unit 2 to 4 m thick that was present in every Cotham Formation outcrop in the UK, and referred to them as a seismite. He concluded that they were the result of a shock wave generated by the impact of a major bolide >600 km west or north-west of central Britain, and that the overlying ripple-marked sandstones were a tsunamite that resulted from the tidal wave that the impact generated. Neither interpretation is supported by the field evidence in the Severn Estuary area.

Small-scale deformation structures are common in the lenticular-bedded mudstones and siltstones that make up the lower part of the Cotham Formation in the Severn Estuary area and elsewhere. The amount of slumping and the stratigraphical levels at which it occurs vary from locality to locality, and over distances of tens of metres within a single exposure. At Lavernock Point, the whole of the Lower Cotham Member and the top part of the Westbury Mudstone is locally slumped, but at St Mary's Well Bay the same beds are undisturbed (Figure 2c). Similarly, there is considerable variation in the thickness and stratigraphical position of the slumped beds on the Somerset coast as noted by Whittaker and Green (1983, figure 12) and in Figure 5. At Lilstock Bay, slumped beds at more than one level pass laterally into undisturbed lenticular-bedded mudstones and siltstones (Figure 4a). The slumped beds in the formation in the Severn Estuary area are best explained as the result of seismic shocks related to small-scale movements on the numerous faults within the Bristol Channel Basin. The sedimentology of the overlying ripple-marked sandstones is indicative of deposition in shallow-marine environments with oscillating currents (Hesselbo *et al.*, 2004), not by a tsunami.

In a study of facies changes in the Penarth Group and basal Lias, Hesselbo *et al.* (2004) concluded that the contact between the Westbury Mudstone and the Cotham Formation was a gradational transition, and that the lower Cotham Formation represented a shoreface equivalent of the Westbury Mudstone. This interpretation was not confirmed in the present study in which an erosion surface and sedimentary break was recorded at the base of the Cotham Formation in every section examined in the Severn Estuary area, in inland Somerset and in Devon (Gallois, 2007). The limited palaeontological evidence available suggests that the hiatus at the junction of the Westbury Mudstone and Cotham Formation does not represent a great length of time. The bivalve and associated fauna of the Westbury Mudstone remained relatively unchanged in the Lower Cotham Member (Waters and Lawrence, 1987, figure 30).

The desiccation surface at the base of the Upper Cotham Member in the Severn Estuary area that Mayall (1983) suggested was the result of local seismic uplift, was interpreted by Hesselbo *et al.* (2004) as evidence of a world-wide fall in sea level followed by transgression. The transgression was shown to coincide approximately with a carbon-isotope excursion that they correlated with the Late Triassic extinction event (Benton, 1995) and with the initiation of massive volcanic eruptions in the mid Atlantic. They further suggested that the low point in the carbon cycle could be used as an isochronous marker to define the Triassic-Jurassic boundary. Large-scale desiccation cracks of the type seen in the Severn Estuary area have not been recorded in sections at Somerton in inland Somerset, nor at this stratigraphical level at Culverhole, Devon (Mayall, 1983).

Stratigraphic unit and description	Thickness (m)
<i>Lias Group: Blue Lias Formation (pars)</i>	
Limestone, bluish grey, argillaceous, tightly cemented	0.11
Mudstone, interlaminated grey and brownish grey, organic-rich, fissile-weathering; sharp, planar base without obvious burrowing	1.40
<i>Watchet Mudstone Formation (0.28 m)</i>	
Mudstone, pale grey, calcareous, subconchoidal weathering; common crushed bivalve fragments; infills hollows in top of underlying bed	0.08 to 0.10
Limestone, medium grey, tightly cemented, argillaceous with abundant moulds of <i>Liostrea</i> , <i>Modiolus</i> and other bivalves	0.08 to 0.10
Mudstone, pale greyish green: infills hollows in uneven top in underlying bed	0.10
<i>White Lias Formation (0.20 to 0.21 m)</i>	
Limestone, dense, micritic, laminated with porcellanous texture; two beds 0.10 m thick separated by a thin (10 mm thick) bed of calcareous mudstone that infills the irregular upper surface of the lower limestone	0.20-0.21
<i>Cotham Formation (2.80 to 3.00 m)</i>	
<i>Upper Cotham Member</i>	
Bed C10: limestone, argillaceous, highly bioturbated with extensive <i>Thalassinoides</i> and other burrow systems; capped by irregular mineralised surface with encrusting oysters	0.07
Bed C9: mudstone, greenish grey, weakly calcareous in part	0.30
Bed C8: mudstone, greenish grey, laterally highly variable with calcareous contents varying from low (weakly cemented mudstone) to high (muddy limestone) to very high (porcellanous limestone) in alternating lenticular and nodular beds 0.02 to 0.10 m thick	0.45
Bed C7: limestone, thinly-bedded and laminated, porcellanous, micritic; readily splits into thin beds	0.08 to 0.12
Bed C6: mudstone, greenish grey, weakly calcareous in part; mostly thinly bedded with laminated clay-rich beds and thicker more calcareous beds	0.50-0.60
Bed C5: Sandstone/calcarenite, fine- and medium-grained with shell debris and siltstone; forms stacked wave ripples with mudstone partings; wavy bedded in part; small-scale patterns of desiccation cracks at several levels; larger scale sand-filled cracks locally extend down from the base	0.33
<i>Lower Cotham Member</i>	
Bed C4: muddy limestone, greenish grey strongly cemented version of bed below; isolated siltstone ripples and thin lenses; locally slumped	0.20
Bed C3: mudstone, greenish grey, weakly calcareously cemented in part; laminated and thinly bedded with silt lenses and isolated ripples of coarse silt; locally slumped	0.60
Bed C2: muddy limestone as Bed C4; locally slumped	0.20
Bed C1: complex laterally variable bed with local slump structures; mostly greenish grey calcareous mudstones and silty mudstones with irregular slumped masses of calcareously-cemented mudstone and streaks and clasts of dark grey mudstone; very irregular base rests with sharp lithological contrast on underlying bed; lag deposit locally at base with common fish debris, sand grains and small black phosphatic pebbles	0.12 to 0.35
<i>Westbury Mudstone Formation (pars)</i>	
Mudstone, dark grey, laminated, pyritic in part; shelly at many levels with common crushed bivalves; beef seams at several levels	1.00 (seen)

Table 4. The succession measured on the wave-cut platform [ST 0989 4370 to 1017 4339] at St Audrie's Bay.

The emergent surfaces that they represent appear, therefore, to be related to local uplift rather than regional or global sea-level change. The current leading candidate for the definition of the base of the Jurassic System is the incoming of the ammonite *Psiloceras spelae* Guex (Hillebrandt *et al.*, 2007). This species is older than the oldest psiloceratids recorded to date in Britain. This implies that the boundary is in the basal beds of the Lias Group or in the highest part of the Penarth Group.

Mander *et al.* (2008) carried out a palaeoecological study across what they assumed to be the late Triassic extinction

event by sampling the shelly invertebrate macrofauna of the Penarth Group and basal Lias at Lavernock Point and St Audrie's Bay. Nine samples were collected from the beds classified here as Cotham Formation, White Lias and Watchet Mudstone. Of these, three came from the Cotham Formation, one from the Lower Cotham Member at St Audrie's Bay and one each from the unfossiliferous Upper Cotham Member at Lavernock Point and St Audrie's Bay. They found little evidence of a catastrophic extinction, but did record a significant palaeoecological change in the benthic marine

ecosystem in which the immediate post-event recovery interval was characterised by bivalve assemblages of low abundance and low diversity.

SUMMARY AND CONCLUSIONS

The latest Triassic in south-west Britain is represented by the Penarth Group, a thin (<20 m thick) succession of shallow-water brackish to marine sediments that can be grouped into four formations, each of which is separated by an erosion surface. In the Severn Estuary area these are, in ascending order, the Westbury Mudstone, Cotham, White Lias and Watchet Mudstone formations. When traced eastwards into inland Somerset, the Westbury Mudstone and Cotham Formations remain little changed, but the White Lias limestones thicken rapidly at the expense of the Watchet Mudstone Formation. Much has been written about the regional and global significance of the environmental and biotic changes represented in the Penarth Group successions of the Severn Estuary area, but none of the published accounts of these studies has fully described the erosion surfaces that bound the formations and the numerous sedimentary breaks that occur within them. These need to be taken into account in any discussion of possible global events, such as sea-level changes, mass extinctions and bolide impacts, close to the Triassic-Jurassic boundary.

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