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Edited by Nicol Morton and Stephen Hesselbo

Jurassic (left) and Triassic (right), Somerset,, England (photo: S. P. Hesselbo)

Contents

PROPOSAL (5 of 6)

SELECTION AND VOTING PROCEDURES FOR THE BASE HETTANGIAN

PREFACE

Nicol MORTON

The ISJS Newsletter no. 34 for 2007 was issued in two parts. Part 1, issued in July (but for free downloading from the website rather than by email attachment because of the large size of the file), was devoted to the Triassic/Jurassic boundary question and contained five of the six proposal documents for selection of the GSSP for the base of the Hettangian Stage and Jurassic System. [The sixth proposal was not completed and submitted until much later.] Part 2, issued in December and distributed in the usual way, contained the usual news items and meetings information, reports from the Working Groups, correspondence and memorials.

For this year 2008 we have decided to follow the same arrangements for the ISJS Newsletter no. 35. Therefore, this issue is Newsletter 35, Part 1 and is also devoted to the Triassic/Jurassic boundary. It contains the sixth proposal, gives a foreword and details of the subsequent discussion and voting procedures, the results of the votes and comments of the Voting Members of the Jurassic Subcommission.

The GSSP (at Kuhjoch section, Austria) and ASSP (at Ferguson Hill, Nevada, USA) were approved by the Jurassic Subcommission in August 2008 but have not yet been examined by the International Commission on Stratigraphy.

The St Audrie's Bay – Doniford Bay section, Somerset, England: updated proposal for a candidate Global Stratotype Section and Point for the base of the Hettangian Stage, and of the Jurassic System

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Abstract

The appearance of the ammonite *Psiloceras planorbis* at the base of bed 13 in the Blue Lias Formation in the coastal cliff section in the headland between St Audrie's Bay and Doniford Bay, west Somerset, is proposed as a candidate Global Stratotype Section and Point (GSSP) for the base of the Hettangian Stage and of the Jurassic System. The level proposed is within a marine succession, corresponds with the base of the lowest classical ammonite subzone and zone of the Hettangian Stage, and is within an ammonite succession that is recognised and correlatable over a wide area. Diverse microfloras and micro- and macrofaunas occur in the succession and provide proxies that enable correlation to other marine sequences and to non-marine successions. A magnetostratigraphic record and a carbon isotope profile and other isotope data provide additional proxies that enable correlation to both marine and non-marine sequences elsewhere. The candidate level is readily identifiable in a cliff section that is clean and freely accessible, and the candidate site is within a protected area that already includes the Sinemurian GSSP, defining the top of the Hettangian Stage.

Contents

1. INTRODUCTION

The section in the headland [UK National Grid Reference ST 1020 4330] that separates St Audrie's Bay from Doniford Bay, on the west Somerset coast, southwest England (Figs 1A,B, 2a,b,d,e,h), was proposed as a candidate Global Stratotype Section and Point (GSSP) for the base of the Jurassic by Warrington *et al.* (1994). Since that time additional biostratigraphic information has accrued and the results of studies of the magnetostratigraphy and of carbon and other isotopes have become available. The inclusion of this data in an update of the original proposal is therefore appropriate and required in order that it may be properly and objectively considered in the vote to select a preferred candidate Hettangian GSSP.

2. BACKGROUND AND HISTORICAL CONTEXT

1859 – Introduction of the term 'Rhaetian', as 'rhätische' (Gümbel, 1859: 84).

1864 – Introduction of the term 'Hettangian' (Renevier, 1864).

1962 – 1st Luxembourg Jurassic Colloquium: participants recommend that the Rhaetian Stage be placed in the Trias, and that the 'Zone of *Psiloceras planorbis*' should be the basal unit of the Hettangian Stage, at the base of the Jurassic (Maubeuge, 1964: 84; Lloyd, 1964: 252). The Hettangian Stage had been designated as the lowest stage of the Jurassic System by Arkell (1956) and Dean *et al*. (1961).

1967 – 2nd Luxembourg Jurassic Colloquium: British workers recommend that the base of the 'Planorbis Zone', at the base of the 'Planorbis Subzone', should be placed at the base of the Blue Lias, marked by the 'Paper Shale' unit of Richardson (1911), in the Watchet area of west Somerset, England, and that a type section be designated in coastal exposures between Blue Anchor [ST 032 435] and Quantock's Head [ST 130 440] (Morton, 1971: 84 (published 1974); see also George *et al*., 1969: 159-160). These recommendations formed a basis for the definition of the base of the Hettangian Stage but a type section was not designated. The international chronostratigraphic subdivision of the Jurassic has, however, been stable since this time (Morton, 2006: 1).

1968 – British workers formally recommend, in a submission to the IUGS in Prague (August, 1968), that the base of the Hettangian 'be taken at the base of the *planorbis* subzone between Blue Anchor and Quantock's Head, Somerset, England (exact location to be decided)' (British National Committee for Geology, 1968: 22). The base of the Blue Lias, marked by the Paper Shale horizon of Richardson (1911), was proposed as the base of the 'Planorbis subzone' and the 'Planorbis Zone' (British National Committee for Geology, 1968: 30).

1980 – The Jurassic Working Group of the Geological Society of London (Cope *et al*., 1980) recommends the appearance of ammonites of the genus *Psiloceras* for defining the base of the Hettangian, in preference to the earlier proposal of the base of a lithostratigraphic unit (British National Committee for Geology, 1968; George *et al*., 1969). This recommendation was made to facilitate international correlation and for consistency with the approach used in recognising Stage and Standard Zone/Chronozone boundaries higher in the Jurassic (Torrens & Getty, 1980; see also Morton, 1971). It was implemented by the Triassic Working Group of the Geological Society of London (Warrington *et al*., 1980: 10) and endorsed by the British Geological Survey, by usage in its publications, and became generally adopted in the UK. The appearance of *Psiloceras* was then thought to be effectively that of *P. planorbis*, the often crushed mode of preservation of which commonly precluded definite recognition of the species, but not of the genus. The level of this appearance was several metres above the base of the marine Lias Group, the lowest beds of which (termed the 'Pre-planorbis Beds', *auctt.*) were thus assigned to the Triassic.

1984 – The re-established International Subcommission on Jurassic Stratigraphy (Chairman Arnold Zeiss) sets up a Working Group on the Triassic-Jurassic Boundary (Convenor René Mouterde, succeeded in 2000 by Geoffrey Warrington) with the task of proposing a Global Stratotype Section and Point (GSSP) for the base of the Hettangian Stage and the Jurassic System.

1991 – The need to select a type section for the base of the Jurassic is highlighted by discussion (Cope, 1991a, b; Poole, 1991) arising from a contribution (Hallam, 1990) in which the boundary was placed at the base of a lithostratigraphic unit, the 'Blue Lias Formation', rather than within that formation, at the appearance of *Psiloceras*, as had become general usage in the UK during the previous decade. A basis for international consideration of the base of the Jurassic, formulated according to the then applicable ICS guidelines (Cowie *et al*., 1986), was clearly necessary.

1994 – Warrington *et al*. (1994) propose, from within the area recommended to the 2nd Luxembourg Jurassic Colloquium (1967) and the IUGS (1968), the appearance of ammonites of the genus *Psiloceras* at the base of bed 13 of the Lias Group succession exposed in a specific section (the headland at [ST 1020 4330], at the west side of St Audrie's Bay, near Watchet, west Somerset) as a candidate GSSP for the base of the Planorbis Standard Subzone/Subchronozone and, *inter alia*, the base of the Planorbis Standard Zone/Chronozone, the Hettangian Stage and the Jurassic System.

1995 – Following the report of *Psiloceras* from beds 8 and 9 in the Lias Group succession in the St Audrie's Bay section (Hodges, 1994), Warrington and Ivimey-Cook (1995) adopt the base of bed 8 as the base of the Planorbis Subzone. That level was also adopted in a zonation in which the Planorbis Subchronozone comprised, in ascending order, the *erugatum*, *imitans*, *antecedens*, *planorbis*, *sampsoni* and *plicatulum* biohorizons (Page & Bloos, 1998; Page, 2005). However, those authors considered that the specimens from beds 8 and 9 are too poorly preserved to permit specific identification, and those in bed 13 thus remain the earliest established *P. planorbis*.

2007 – The authors of the present, updated, proposal again advocate the appearance of the first definite *Psiloceras planorbis*, at the base of bed 13 in the Lias Group succession exposed in the headland at the west side of St Audrie's Bay, as a candidate GSSP for the base of the Planorbis Subchronozone and, *inter alia*, the base of the Planorbis Chronozone, the Hettangian Stage and the Jurassic System.

In the above review the orthography used for the ammonite zones and subzones is inconsistent (e.g. 'Planorbis Subzone' appears in a 1967 article, and '*planorbis* subzone' and 'Planorbis subzone' in one from 1968); under current convention this signifies usage in both chrono- and biozonal senses for the same unit. The issue of the use of Jurassic ammonite zones as chronozones, rather than biozones, was addressed exhaustively, and authoritatively, by Callomon (1995), and reviewed by others (e.g. Cox, 1990: 169-172; Morton, 2006: 4-5). In the remainder of this proposal chronostratigraphic usage is followed (unless different in quoted material); this is in accordance with the principle urged at the 1967 Luxembourg Jurassic Colloquium (Morton, 1971: 83) and recommended to the IUGS (British National Committee for Geology, 1968: Appendix B3, 27-30), that Standard Stages should be defined in terms of Standard Chronozones, with the base of a stage being defined in a GSSP by the base of its lowest constituent chronozone. As Jurassic stages are accepted as 'Standard Stages', though several do not yet have a GSSP, there is no intrinsic difference in interpreting the constituent zones and subzones, some of which also lack a basal stratotype, as standard chronostratigraphic units (chronozones and subchronozones). In this proposal therefore, the use of 'Planorbis Zone' and 'Planorbis Subzone', for example, signifies reference to the Planorbis Chronozone and the Planorbis Subchronozone respectively. The units recognised in Europe are generally regarded as a global standard to which other regional zonal schemes are calibrated (Morton, 2006: 6).

3. LOCATION AND ACCESS

The section is located at the north end of the sea cliff at the west side of St Audrie's Bay, west Somerset, England [ST 1020 4330] (Figs 1A,B).

The site is a headland (Fig. 2a) on the south side of the Bristol Channel, separating St Audrie's Bay, to the east, from Doniford Bay, to the west (Fig. 1B). Exposure of the succession seen here in vertical section (Figs 2b,d,e,h) continues southeastwards for c.200 m in a strike-section in the cliff (Fig. 2a) at the west side of St Audrie's Bay, and westwards, into Doniford Bay (Figs 2h,i). Bedding surfaces in the same beds are exposed on the adjacent foreshore (e.g. Fig. 2g). The stratigraphic succession is continuous downwards, to the east, in St Audrie's Bay (Figs 2b,c), and upwards, to the west, in Doniford Bay (Figs 2h,i). Some 116 m of strata are seen below the level of the candidate GSSP in the cliffs between St Audrie's Bay and Blue Ben (Fig. 1B), and c.70 m are seen above that level in cliffs in Doniford Bay (see **4**).

Topographical maps: UK Ordnance Survey 1:50 000-scale sheet 181 (Minehead and Brendon Hills) and 1:10 560-scale sheet ST 14 SW.
Geological maps (Fig. 1A): British Geological Survey 1:50 000-scale sheets 279 (Weston-super-Mare, 1980; including parts of sheets 263 (Cardiff) and 295 (Taunton), and with a 1:10 560-scale detailed inset map of St Audrie's Bay), and 295 (Taunton, 1975).

The locality is within the area recommended by the Jurassic Working Group of the Mesozoic Era Subcommittee of the Geological Society of London (George *et al*., 1969; Morton, 1971), and by the British National Committee for Geology (1968) in a submission to the IUGS, for the basal stratotype of the Hettangian Stage. A clean section (Figs 2b,d,e) is permanently exposed in a near-vertical sea cliff, with corresponding bedding surfaces visible on the contiguous foreshore (e.g. Fig. 2g), and is accessible except at times of high tide; access to the section is otherwise unrestricted. The locality is in a Site of Special Scientific Interest (SSSI) that extends from Blue Anchor eastwards for c.19 km to Lilstock [ST 195 462] (Fig. 1B). The SSSI was notified to the then British Parliamentary Secretary of State on 22 December 1986 and enjoys statutory protected status in UK law under Section 28 of the Wildlife and Countryside Act 1981 (as amended). The locality is also included in the Geological Conservation Review of British sites of national and international importance carried out by the UK Joint Nature Conservation Committee (Benton *et al.*, 2002; Simms, 2004).

The Sinemurian GSSP, defining the top of the Hettangian Stage, is already established within this SSSI, on the coast at Limekiln Steps [ST 137 443] near East Quantoxhead, c.3.5 km east-north-east of the Hettangian candidate site (Page, 2001; Bloos & Page, 2002) (Figs 1B, 2j). A close link between these sites is provided by the presence of the boundary between the Angulata and Bucklandi zones in Doniford Bay, in a section contiguous with the candidate Hettangian GSSP (see ***5.3.1***, ***6.1.1***).

St Audrie's Bay is readily accessible by public and private transport. Taunton (Fig. 1A: 22 km) is served by mainline rail and express coach services from most parts of Britain, including towns such as Birmingham, Bristol, Cardiff, Edinburgh, Exeter, Glasgow, London, Manchester and Nottingham that have airports with regional and/or international services. A bus service from Taunton to Minehead serves Watchet, c.3 km west of St Audrie's Bay (Figs 1A,B). A bus service from Taunton to Bishops Lydeard connects with the privately-run West Somerset Railway which serves stations at Williton and Doniford Bay, c.2.5 km southwest and c.2 km west of St Audrie's Bay respectively, and Watchet, c.3 km west of St Audrie's Bay and <1 km west of Doniford Bay. The M5 motorway (junctions 23 and 24) serves Bridgwater, from where the A39 leads to West Quantoxhead, and Taunton (junction 25), from where the A358 leads to Bicknoller for West Quantoxhead. Access to a 'pay and display' car park [ST 105 430] above St Audrie's Bay is at Rydon [ST 100 424], on a minor road leading to Watchet from the A39 at [ST 105 420] at the west side of West Quantoxhead. St Audrie's Bay is reached on foot from the car park via a short but steep paved track that leads to steps to beach level at [ST 1055 4311], c.420 m southeast of the candidate GSSP site.

Access to St Audrie's Bay is unrestricted. However, as it is within an SSSI, staff of Natural England (formerly English Nature) in Taunton (somerset@naturalengland.org.uk) must be consulted before sampling and collecting programmes are planned.

The tidal range in the Bristol Channel is considerable and may exceed 12 m. The times of low and high tide ***must*** be ascertained when planning a visit to the site (consult: http://www.bbc.co.uk/weather/coast/tides/west.shtml; port 531–Watchet). The rising tide advances rapidly across the flat-lying foreshore, and access from the steps leading from the track from the car park is usually not possible for a short period before or after high-tide.

4. GEOLOGICAL SETTING

The candidate Hettangian GSSP lies within a sequence of Late Triassic and Early Jurassic rocks that are exposed continuously in sea cliffs over a distance of about 3 km, from near Blue Ben [ST 1200 4375] westwards to [ST 092 433] in Doniford Bay (Figs 1B, 2a-e,h-i). Bedding surfaces in this sequence (e.g. Fig. 2g) are exposed on the adjacent foreshore, in a broad wave-cut platform. The beds dip generally southwestwards at between 9 and 18°, with 13 to 14° being recorded near the candidate GSSP. Younger beds appear progressively westwards in the cliffs and, as a consequence of the prevailing dip, become accessible sequentially at beach level (Figs 2c,b,h,i). Some 200 metres of strata comprising, from east to west, the upper part of the Mercia Mudstone Group, the Penarth Group, and the lower part of the Lias Group, are seen in the cliff and foreshore exposures (Whittaker & Green, 1983). This succession represents a change from continental to marine environments as a result of a transgression that commenced during the deposition of the highest Mercia Mudstone Group formation (see ***5.1.2***). The transgression was punctuated by minor regressions but marine conditions were established well before the inception of Lias Group deposition. The succession seen in the cliffs ranges in age from Late Triassic (Norian: Briden & Daniels, 1999; Hounslow *et al*., 2004; Gallet *et al*., 2007, fig. 6; Kemp & Coe, 2007) to Early Jurassic (late Hettangian, Angulata Zone) (Whittaker & Green, 1983; Warrington & Ivimey-Cook, 1995). Higher beds, extending into the Bucklandi Zone (early Sinemurian), crop out on the foreshore in Doniford Bay (Fig. 2j), and younger beds, in the Semicostatum Zone, are exposed nearby, at [ST 0783 4325] in Helwell Bay (Whittaker & Green, 1983: 63-64, 66).

The coast between Blue Ben and Doniford Bay, including St Audrie's Bay, provides the most extensive and continuous exposure of the Late Triassic to Early Jurassic sequence on the west Somerset coast and has been subject to detailed study for more than 130 years. Notable early contributions include those by Bristow and Etheridge (1873, Section No.6, St Audrie's Slip) and Richardson (1911); more recent documentation has been provided by Palmer (1972) and the British Geological Survey (Whittaker & Green, 1983; Edmonds & Williams, 1985; Edwards, 1999). Watchet, c.3 km west of St Audrie's Bay (Figs 1A,B), is the type locality for *Psiloceras planorbis*, the index fossil of the lowest Hettangian Standard Zone (Donovan, *in* Donovan & Hemingway, 1963: 270). The lectotype of this fossil (Fig. 2f), figured by J. de C. Sowerby (1824: 69; pl.448, upper figure)), is housed in the Natural History Museum, London. Specimens of this ammonite are common in beds of the Planorbis Subzone in the Watchet area, including those at the candidate GSSP site (Fig. 2g). Page (2005: 16) considered that the lectotype probably originated from the *planorbis* biohorizon (Fig. 5) in or west of Doniford Bay, as aragonitic preservation of that species is not found farther east.

The succession containing the candidate GSSP dips southwestwards on the northern limb of the Doniford Bay Syncline (Whittaker & Green, 1983: 66). Small-scale faulting affects the Blue Lias Formation (Lias Group); a low-angle thrust repeats part of the succession in the cliff at [ST 1029 4319], and strike faulting repeats part of the succession on the foreshore at [ST 1013 4334] (Whittaker & Green, 1983: 66, 101). Small, high-angle reverse faults occur in the Mercia Mudstone Group but have little effect on the general structure. Incompetent mudstones in the Westbury Formation (Penarth Group) tend to act as a locus for strike faults, and the junction of this formation with the overlying Cotham Member (Lilstock Formation; Penarth Group) is faulted in places (Whittaker & Green, 1983: 42, 55, 101). Foreshore outcrops in Doniford Bay (Fig. 2j) are on the southern limb of the Doniford Bay Syncline and the northern (upthrow) side of the normal Doniford Bay Fault (Whittaker & Green, 1983: 101; geological maps (see **3**)). The faulting in the area of the candidate GSSP is small-scale and does not impede interpretation of the succession or identification of the candidate GSSP level.

5. STRATIGRAPHY

5.1. Mercia Mudstone Group

The upper part of this group, represented by the upper part of the Branscombe Mudstone Formation (Howard *et al*., in press; implemented *in* Hounslow & Ruffell, 2006, and Kemp & Coe, 2007), formerly the Twyning Mudstone Formation (e.g. Hounslow *et al*., 2005: 333), and the succeeding Blue Anchor Formation, is exposed in cliffs and the adjacent foreshore from Blue Ben westwards for about 1.7 km to St Audrie's Bay (Figs 1B, 2c,b).

5.1.1. Branscombe Mudstone Formation

This unit is exposed in cliffs to the east of the access to the beach at [ST 1055 4311] and to c.30 m west of that point (Figs 2c,b). It comprises c.67 m of red-brown dolomitic mudstone and siltstone with, in the upper 37 m, numerous beds of green or greenish-grey mudstone and siltstone that are mostly <0.5 m thick; a 4 m-thick bed with dark grey mudstone intercalations occurs between 15 and 11 m below the top of the formation (Whittaker & Green, 1983). Talbot *et al*. (1994) considered that these sediments are floodplain and playa deposits that accumulated in arid or semi-arid continental environments of low relief; sulphates and thin carbonate units were also noted and interpreted as having formed as partly pedogenic precipitates and in temporary bodies of fresh or brackish water respectively.

The formation is largely unfossiliferous; bioturbation and rootlet traces occur, and a chlorococcalean alga (*Botryococcus*) and charophyte remains are present in some of the carbonate units (Talbot *et al*., 1994). Miospores were recovered from the upper 15 m of the formation (see ***6.3.1***). Magnetostratigraphic and gamma-ray profiles (see **7** and **12**) and chemostratigraphic data (see **8**) are available; a cyclostratigraphic study has provided astronomical calibration of part of the magnetostratigraphic record (see **11**).

5.1.2. Blue Anchor Formation

This unit is 31.18 m thick at St Audrie's Bay (Whittaker & Green, 1983) where it is exposed in cliffs between c.30 and 140 m west of the access to the beach at [ST 1055 4311] (Fig. 2b); it comprises the Rydon and overlying Williton members (Mayall, 1981).

The Rydon Member (c.29 m) comprises grey, black, green and, rarely, red-brown dolomitic mudstone and, mainly towards the top of the member, dolomite. Also present are silt-laminated beds with mudcracks, scarce pseudomorphs after halite, and features resulting from dissolution of gypsum. Corrensite is present in this member, but not in the succeeding Williton Member (Mayall, 1979, 1981; see **9**). The organic geochemistry of the upper 9 m of the Rydon Member suggests a passage from playa or supratidal sabkha environments, in which the lower 20 m were deposited, to marginal marine conditions (Thomas *et al*., 1993); bivalves, gastropods and fish remains are recorded from the upper 2 m at St Audrie's Bay (Whittaker & Green, 1983: 50; Warrington & Whittaker, 1984). The upper part of this member therefore represents the earliest manifestation of a marine transgression. The top of the member is a disconformity marked by an irregular erosion surface penetrated by *Diplocraterion* burrows (Mayall, 1981). Miospores were recovered from the member (see ***6.3.1***). Magnetostratigraphic and gamma-ray profiles (see **7** and **12**) and chemostratigraphic data (see **8**) are available.

The Williton Member is c.2 m thick in its type section, at St Audrie's Bay. It comprises grey shale with flaser- and lenticular-bedded fine sand and silt; mudcracks and synsedimentary faults occur. Fish remains and a bivalve are recorded from St Audrie's Bay (Whittaker & Green, 1983: 51; Warrington & Whittaker, 1984) and bioturbation is well developed (Mayall, 1981). Palynomorphs recovered include miospores and, near the top of the member, dinoflagellate cysts (see ***6.3.1***, ***6.3.2***). Sedimentary and biotic evidence indicates that this member was deposited in a shallow marine environment. Magnetostratigraphic and gamma-ray profiles (see **7** and **12**) and chemostratigraphic data (see **8**) are available.

5.2. Penarth Group

This group comprises the Westbury Formation and the overlying Lilstock Formation (Figs 3, 4). It appears at the top of the cliff on the south side of St Audrie's Bay (Fig. 2b) and reaches beach level in the southwest corner of that bay, where it is periodically partly obscured by landslip. Exposure of the upper part extends part-way along the foot of the cliff at the west side of the bay (Fig. 2a); the succession also crops out on the adjacent foreshore.

5.2.1. Westbury Formation

Thicknesses given for this formation at St Audrie's Bay are 9.6 m (Hesselbo *et al*., 2004a, fig. 4)[1], 10.6 m (Richardson, 1911), and between 10.15 and 10.48 m (Whittaker & Green, 1983)[2]. The formation consists largely of dark grey and black shaly mudstone, some with wisps and partings of grey-green mudstone or siltstone. Subordinate lithologies include silty calcareous mudstone, dark grey argillaceous limestone, rippled sandstone, pebbly sandstone and bone beds. Three sedimentary cycles, representing alternating deposition in transgressive, littoral, high-energy environments and lower energy, stagnant or weakly oxygenated water bodies, may be present (Whittaker & Green, 1983: 43). Sykes (1977) described and discussed the bone beds at St Audrie's Bay (*ibid*.: 226-230, Pl.14, fig. 6) and nearby, at Blue Anchor and Lilstock (Fig. 1B); detrital quartz grains in a bone bed at Blue Anchor show diagenetic solution and the formation of overgrowths (Antia & Sykes, 1979). Macquaker (1994) and Martill (1999) reviewed the origin and other aspects of Westbury Formation bone beds. Macquaker (1984) discussed the diagenetic modification of primary sedimentary fabrics in the Westbury Formation at St Audrie's Bay and later (1999) reviewed aspects of its sedimentology. Macquaker *et al*. (1986), Thomas *et al*. (1993) and Tuweni and Tyson (1994) documented the organic geochemistry of black shale lithologies in the formation. Palynomorphs, including miospores and marine organic-walled microplankton, are present, in addition to marine micro- and macrofaunas, the latter dominated by bivalves (see **6**). Magneto- and chemostratigraphic data (see **7** and **8**) are available.

5.2.2. Lilstock Formation

This calcareous unit is c.3 m thick at St Audrie's Bay where the lower (Cotham) and upper (Langport) members are both c.1.5 m thick (Whittaker, 1978; Mayall, 1983; Whittaker & Green, 1983).

The Cotham Member comprises pale grey and greenish grey calcareous mudstone with ripple lenses, limestone, siltstone and sandstone; it is broadly fining-upward in character. The

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[1] Based on measurement of Richardson's (1911) beds 15 to 25 in the cliff section and the higher beds (5 to 14) in foreshore exposures (Dr S. P. Hesselbo, *pers. comm*. to GW, September 2007).

[2] Dr S. P. Hesselbo (*pers. comm*. to GW) courteously drew attention to the possibility that the thickness (12.6m) given by Warrington *et al*. (1994) and Warrington and Ivimey-Cook (1995) is too high.

junction with the underlying Westbury Formation is irregular in places (Whittaker & Green, 1983: 44). A prominent c.0.5 m-thick unit of deformed beds occurs in the middle of the member and is overlain by an erosion surface penetrated by deep cracks infilled with sediments similar to those overlying the deformed unit (Figs 3, 4). The member formed in shallower water than the Westbury Formation. The deformed unit is interpreted as a seismite and the cracks penetrating it are considered to reflect temporary emergence (Mayall, 1983; Simms, 2003, 2007). Conditions of deposition were, however, generally subaqueous and at least partly marine. Palynomorphs, including miospores and marine organic-walled microplankton, are present, in addition to marine micro- and macrofaunas (see **6**). Magneto- and chemostratigraphic data (see **7** and **8**) are available.

The Langport Member consists largely of pale grey limestone with interbedded grey or blue-grey mudstone. In the lower part of the member the limestone is commonly lenticular or nodular, locally porcellanous or laminated. The higher beds include two or three cream-weathering limestones that form a unit with an irregular base. The highest of these limestones (the 'Sun Bed') is bored and in places has an irregular upper surface; U-shaped burrows are seen locally (Whittaker & Green, 1983: 42, 44, fig. 12). The succession above this level, comprising the 'Watchet Beds' overlain by the Lias (Richardson, 1911: 21), was revised by Whittaker (1978) who transferred the upper 1.42 m of bed 1 of Richardson's 'Watchet Beds' to the Lias, as bed 1 of the 'Pre-planorbis Beds', and amalgamated the lower 0.34 m (beds 1 (*pars.*), 2 and 3 of Richardson, *op. cit.*) into the Lilstock Formation (Whittaker & Green, 1983: 44, 54, fig. 12) (see **18**). Deposition occurred in warm, very shallow water in saline lagoonal environments. Hallam and Wignall (2004) considered that micrite clasts in the basal 0.02 m of the Blue Lias Formation indicated a sharp regression, followed by a rapid transgression, at the Lilstock Formation – Blue Lias Formation boundary. Hesselbo *et al.* (2004b), however, suggest that early lithification evident in the Langport Member does not imply subaerial exposure, and that fragmentation of early-lithified carbonate could result from slope-related gravity transport. Palynomorphs, including miospores and marine organic-walled microplankton, are present, in addition to marine micro- and macrofaunas (see **6**). Magneto- and chemostratigraphic data (see **7** and **8**) are available.

5.3. Lias Group

The Lias Group succession exposed in the cliffs for c.1.2 km from St Audrie's Bay to Doniford Bay (Figs 2a,h,i) comprises c.74 m of the Blue Lias Formation, up to a level in the Hettangian Angulata Zone (Whittaker & Green, 1983: 66, 68) (see **18**). This formation is partly seen in the strike-section in the cliff at the west side of St Audrie's Bay and reaches beach level near the north end of that cliff (Figs 2a,b,d.e.h). From that point the exposure of the formation continues westwards for about 1 km, to [ST 092 433] in Doniford Bay, with successively younger beds appearing in the cliffs and, in consequence of the westerly dip, reaching or approaching beach level (Figs 2h,i). Higher beds in the formation are exposed on the foreshore in Doniford Bay (Fig. 2j). The Blue Lias Formation extends up into the Semicostatum Zone which crops out nearby at [ST 0783 4325] in Helwell Bay (Whittaker & Green, 1983: 63-64, 66); higher beds seen in Helwell Bay are assigned to the succeeding Charmouth Mudstone Formation (Cox *et al.*, 1999: 9). Bed numbers used in this account are those of Whittaker and Green (1983: 62, fig. 13), who recognised the following lithological units in the Lias Group in west Somerset:

5. Mudstone and shale with some argillaceous limestone (beds 204 to 257+), c.80 m (*Blue Lias Formation (pars.) - beds 204 to 238; Charmouth Mudstone Formation (pars.) - beds 239 to 257* (Cox *et al.*, 1999)).

4. Fissile shale and mudstone with a few limestone beds in the middle and upper parts; alternating shale and limestone in the lower part (beds 147 to 203), c.40 m
3. Alternating limestone and shale; individual beds become thicker and more massive towards the top (beds 69 to 146), c.50 m
2. Dark shale and mudstone with nodular limestone horizons (beds 40 to 68), c.20 m
1. Alternating limestone and shale (beds 1 to 39), c.13 m

The succession comprises rhythmic sedimentary units of organic-rich shale, mudstone and limestone. The shale may be bituminous and is commonly pyritic. The mudstone is non- or only weakly fissile, medium to dark grey, blocky and calcareous. The limestone is dark bluish grey, homogeneous, hard, compact and splintery; it occurs mostly in thin, laterally persistent beds, some of which are lenticular, but also forms laterally persistent horizons of nodules. Diagenetic redistribution of carbonate occurred but was insufficient to damage or obscure fossils and ichno- and other fabrics in the sediments. The presence of pyrite and a paucity or lack of benthic fauna and burrowing organisms in the shale units reflect anoxic sea-floor and substrate conditions, whereas the succeeding calcareous mudstones and carbonate-rich beds with a benthic fauna reflect oxygenated conditions (Whittaker & Green, 1983; Hesselbo *et al.*, 2004a).

Units 1 to 4 (up to bed 158) are seen in cliff and foreshore exposures at St Audrie's Bay and Doniford Bay (Figs 2a,b,d,e,h,i). Up to bed 39 the succession includes c.28% limestone, with numerous relatively thick and prominent beds present between 1.42 and 7.5 m above the base (beds 2 to 22), and thinner beds and a nodular development in the upper 4.48 m (beds 25 to 39) (Figs 2d,e, 3). Limestone constitutes only about 3.5% of Unit 2 in which it occurs mainly as nodules in four laterally persistent levels but is also present in thin beds in the basal c.0.25 m and c.5.75 m below the top. Limestone forms c.20% of Unit 3 in which it is more evenly distributed than in Unit 2 and occurs mostly in beds; nodular developments are scarce (Whittaker & Green, 1983, fig. 13) (see **18**). Only c.10% of Unit 4 consists of limestone that occurs mainly in thin beds grouped at four levels in the lower c.21 m (beds 147 to 179); in the upper part of this unit it is more evenly distributed, but is generally in thinner beds than in the lower part (Whittaker & Green, 1983, figs 13, 14). Limestone forms only about 4% of Unit 5; it occurs as beds in the lower c.26 m (beds 204 to 238, top of the Blue Lias Formation) and as nodules at three levels in the higher beds (Charmouth Mudstone Formation) (Whittaker & Green, 1983, fig. 14).

Beds 1-12 in the Blue Lias Formation have generally been referred to as the 'Pre-planorbis Beds', as they were considered to be below the lowest occurrence of *Psiloceras planorbis*, in bed 13. Ammonites, including *P.* cf. *planorbis*, are now known from the upper part of the 'Pre-planorbis Beds' (see ***6.1.1***) and this term is not, therefore, used in this proposal, except in quoted material.

Beds 1 to 7 of the Blue Lias Formation have not, at present, yielded ammonites, the lowest record of which is from bed 8 (Hodges, 1994) (Figs 2e, 3, 5). Definite *Psiloceras planorbis* appear in a 0.61 m-thick shale unit (beds 13-15; Fig. 2e) between 5.42 and 6.03 m above the base of the formation (see ***6.1.1***; Whittaker & Green, 1983: 68). *On the criterion advocated in this proposal the base of the Hettangian would be at the base of bed 13, at the base of this shale unit* (see **14**). Above this level the exposure of the formation in the St Audrie's Bay to Doniford Bay cliff section includes the Planorbis, Liasicus, and part of the Angulata zones (Whittaker & Green, 1983: 66, 68, fig. 13; Ivimey-Cook & Donovan, 1983). Higher beds in the Angulata Zone, succeeded by part of the early Sinemurian Bucklandi Zone, are exposed on the foreshore in Doniford Bay (Whittaker & Green, 1983: 63, fig. 13) (see ***6.1.1***; Fig. 2j).

Beds 1 to 7 include two prominent limestone beds and several thinner ones (Figs 2d,e) that form c.22% of this part of the section. From bed 8 to the top of the Planorbis Zone (bed 42), limestone, comprising four prominent beds in the lower 2.48 m (beds 8 to 22, Fig. 2e), and thinner beds and a nodular development in the upper 4.76 m (beds 25 to 42; Figs 2d,e,h, 3), forms c.30% of the section. Limestone is less abundant in the Liasicus Zone, where it occurs mainly in the upper c.7.9 m (beds 69 to 79) and bedded, discontinuous and nodular developments comprise c.38% of the succession; in beds 43 to 68 it occurs mainly as nodules at four laterally persistent levels (Whittaker & Green, 1983, fig. 13) (Fig. 2h; see **18**). Limestone, mostly bedded, is more evenly distributed in the Angulata Zone where it forms c.19% of the succession (Whittaker & Green, 1983, figs 13, 14, plate 11) (Fig. 2i). Limestone beds form about 28% of the part of the Bucklandi Zone (early Sinemurian) seen on the foreshore in Doniford Bay (Whittaker & Green, 1983, figs 13, 14).

Palynomorphs, including miospores and marine organic-walled microplankton, are present, in addition to marine micro- and macrofaunas (see **6**). Magneto- and chemostratigraphic data (see **7** and **8**) are available from the lower part of the exposed succession, and a gamma-ray profile (see **12**) from the whole of that succession.

6. BIOSTRATIGRAPHY

Until a GSSP for the base of the Hettangian is ratified it is inappropriate for any fossils from a candidate GSSP section to be referred to as ‘Triassic’ or ‘Jurassic’. This is avoided in this proposal where, for example, there is no presumption that all psiloceratid ammonites are ‘Jurassic’.

6.1. Macrofauna

6.1.1. Ammonites

Whittaker and Green (1983) recorded the lowest occurrence of ammonites, represented by abundant *Psiloceras planorbis*, in a shale unit (beds 13 to 15 of the Blue Lias Formation; Fig. 2e) at St Audrie’s Bay (see **18**). Ammonites identified as ‘*P. planorbis*’ and ‘*P.* cf. *planorbis*’ were later recovered slightly lower, in beds 9 and 8 of the Blue Lias Formation respectively, at that site (Hodges, 1994); however, this material was sparse and considered too poorly preserved to permit specific identification (Page & Bloos, 1998: 231; Bloos & Page, 2000: 32). Additional specimens recovered from beds 8, 9 and 13 in Doniford Bay were identified as *Psiloceras erugatum*, *Neophyllites*, and *P. planorbis* respectively (Bloos & Page, 1997a, b); the determinations from bed 8 were later amended to *Psiloceras* cf. *erugatum* (Page & Bloos, 1998: 232, fig. 2; Bloos & Page, 2000, fig. 5), and those from bed 9 to *Neophyllites* sp. (?*N. antecedens*) (bed 9, lower part) and *P.* cf. *planorbis* (bed 9, upper part) (Bloos & Page, 2000: 32; Page, 2005: 16). Prior to this work the stratigraphic relationships of *P. erugatum* and *P. planorbis* had been uncertain; A record (Donovan, *in* Poole & Whiteman, 1966: 50, 119, pl.6) of ‘*Psiloceras planorbis erugatum*’ below *P. planorbis* in the Wilkesley Borehole, Cheshire, has been generally overlooked.

No ammonites have yet been recorded below bed 8 in the Blue Lias Formation, or from older formations, in St Audrie’s Bay and Doniford Bay. The only ammonite attributed to an older formation in the whole of the UK is a small (3.8 mm-diameter) psiloceratid reported from the topmost bed of the Westbury Formation (Penarth Group) in a quarry [ST 726 839] near Chipping Sodbury (Fig. 1A), Gloucestershire (Donovan *et al.*, 1989).

The base of the Hettangian had, following the recommendations of Torrens and Getty (*in* Cope *et al.*, 1980), been placed at the base of bed 13 in the St Audrie's Bay section (Warrington *et al.*, 1994). Following the report of *Psiloceras* cf. *planorbis* in bed 8 and *P. planorbis* in bed 9 in that section (Hodges, 1994), Warrington and Ivimey-Cook (1995: 15) adopted the base of bed 8 as the base of the Planorbis Zone. However, as specimens from beds 8 and 9 were considered too poorly preserved to permit specific identification (Page & Bloos, 1998; Bloos & Page, 2000), those in bed 13 remain the earliest established *P. planorbis*. *In the present, updated, proposal the base of bed 13 is, therefore, again chosen as the candidate GSSP level for the base of the* Planorbis Subchronozone*, the* Planorbis Chronozone*, and the Hettangian Stage* (see **13**, **14**; Fig. 5).

Above the Planorbis Zone, as advocated here (beds 13 to 42; c.7.9 m), the Liasicus Zone (beds 43 to 79; c.28.5 m) and part of the Angulata Zone (beds 80 to 135; c.32.8 m) (Whittaker & Green, 1983: 66, 68, fig.13) (see **18**) are exposed in the cliff at and extending westwards from the candidate GSSP into Doniford Bay (Figs 2h,i) where higher beds in the Angulata Zone (beds 136 to 145; c.8.4 m), succeeded by part of the lower Sinemurian Bucklandi Zone (beds 146 to 158; c.7.5 m), are exposed on the foreshore (Whittaker & Green, 1983: 63, fig.13) (Fig. 2j). The base of the Bucklandi Zone marks the top of the Hettangian Stage as defined in the Sinemurian GSSP [ST 137 443], c.3.5 km east-north-east of the candidate Hettangian GSSP site (Page, 2001; Bloos & Page, 2002) (Fig. 1B; see **3**).

6.1.2. Bivalves

Bivalves recorded from the St Audrie's Bay – Doniford Bay section comprise only marine taxa. They appear near the top of the Blue Anchor Formation and are the most abundant macrofossils in the succeeding Westbury Formation, but are scarcer in the Lilstock and Blue Lias formations. The faunas were reviewed by Whittaker and Green (1983) and Warrington and Ivimey-Cook (1995), principally from records by Bristow and Etheridge (1873), Richardson (1911), Mayall (1981) and Hodges (1994).

A sequence of changes through time and in response to environmental changes, as reflected in lithological differences within and between formations, is evident in these faunas and is documented consistently throughout the eastern Bristol Channel region (Ivimey-Cook, 1974; Donovan & Kellaway, 1984; Waters & Lawrence, 1987; Edmonds & Williams, 1985; Kellaway & Welch, 1993; Warrington & Ivimey-Cook, 1995; Edwards, 1999; Ivimey-Cook *et al.*, 1999). The principal changes are the disappearance of the two characteristic '*Contorta* Zone' bivalves *Rhaetavicula contorta* and *Lyriomyophoria postera* in the lowest part of the Lilstock Formation and a change in the composition of the faunas, and reduction in their diversity, within that formation (Fig. 6). Such changes may be related primarily to environmental variations and, with few exceptions, have only limited stratigraphic value.

The upper 3.7 m of the Blue Anchor Formation has yielded a few poorly preserved bivalves; these have been assigned to *Mytilus* sp.? and *Protocardia rhaetica*, from the Rydon Member, and *Gervillella praecursor*, from the Williton Member (Bristow & Etheridge, 1873, Section 6; Richardson, 1911: 24; Mayall, 1981; Whittaker & Green, 1983: 50, 51; Warrington & Whittaker, 1984) (see ***5.1.2***; Fig. 6).

The Westbury Formation yields the most varied and abundant faunas, with an increase in diversity and numbers upwards (Fig. 6). The dark shaly mudstones often yield abundant *Rhaetavicula contort*a, together with *Gervillella praecursor*, *Isocyprina* (*Eotrapezium*) spp., *Lyriomyophoria postera*, *'Permophorus' elongatus*, *Protocardia rhaetica*, *Ryderia titei* and *Tutcheria cloacina*. *Cardinia* sp., *Chlamys valoniensis*, *Liostrea* sp.?, *Modiolus* spp., *Placunopsis alpina* and *Pteromya* cf. *crowcombeia* are most commonly found in the more calcareous beds. Generally, in the eastern Bristol Channel region, many of these taxa also occur in the lowest c.0.6 m of the overlying Cotham Member, in bed 4(3) of Richardson (1911: 22) and equivalents (Warrington & Ivimey-Cook, 1995; Ivimey-Cook *et al*. 1999). In St Audrie's Bay and Doniford Bay these include *Cardinia* cf. *regularis*, *Chlamys valoniensis*, *G. praecursor*, *I.* (*E*) *concentricum*, *Placunopsis alpina*?, *Protocardia rhaetica* and *T. cloacina*, together with *Atreta intusstriata*, but *R. contort*a has not been recorded (Richardson, 1911: 22; Whittaker & Green, 1983: 54) (Fig. 6). Elsewhere, however, *R. contort*a ranges into the lower part of the Cotham Member, but no higher (Ivimey-Cook *et al*., 1999: 91).

Around St Audrie's Bay bivalves are relatively sparse numerically in the higher part of the Cotham Member and in the Langport Member but *Atreta intusstriata*, *Grammatodon lycetti*, *Liostrea hisingeri*, *Modiolus* spp., *Myoconcha psilonoti*, *Plagiostoma* spp. and *Protocardia* sp. occur there; elsewhere in the region *Astarte*, *Camptonectes*, *Cardina*, *Gervillella*, *Pholodomya and Pteromya* are also present. These genera continue upwards into and through the Blue Lias Formation. *Antiquilima* appears in the lowest beds of the Blue Lias Formation; *Protocardia rhaetica* ranges up into those beds (Warrington *et al*., 1995: 429) and appears to be succeeded by *Protocardia philippianum* in that formation (Warrington & Ivimey-Cook 1995). Bivalves are scarce in many of the shalier beds in the Blue Lias Formation but *Liostrea* and *Modiolus* are locally abundant on the surfaces of limestone beds. Some new genera, including *Anningella, Gryphaea*, *Lucin*a, *Mactromya* and *Pinna*, appear in, and range upwards through, the Blue Lias Formation.

The stratigraphic value of the bivalves may be limited because of environmental influences. However, an exception may be *Rhaetavicula contort*a, the LAD of which is in the lower part of the Cotham Member (Ivimey-Cook *et al*., 1999: 91). This bivalve characterises the '*Contorta* Zone', which appears to occupy a relatively constant stratigraphic position in northwest European successions and may provide a regional reference datum. However, as the LAD of *R. contorta* occurs below a stratigraphic gap marked by the Sequence Boundary above the deformed unit in the Cotham Member (see ***5.2.2***, **10**), it provides only a general indication of an horizon below the candidate GSSP level and is not proposed as a proxy for that level. A more satisfactory proxy in this part of the succession is provided by the 'Initial Isotope Excursion' of Hesselbo *et al*. (2002), which occurs slightly higher in the Lilstock Formation, and close above the Sequence Boundary (see **13.2**; Figs 4, 14). Changes in bivalve associations from the Blue Lias Formation at St Audrie's Bay and Doniford Bay may broadly characterise the candidate GSSP level there but are not proposed as proxies; these include the FADs of *Pteromya tatei*, *Antiquilima succincta*, cf. *Anningella* and *Anningella faberi* in beds 5, 7, 13-15 and 23-24 respectively (Fig. 6).

In sections in Tibet, bivalves known from 'the basal Jurassic of England (e.g. *Chlamys valoniensis* and *Plagiostoma giganteum*)' occur in the 'main bivalve bed' in the *tibeticum* ammonite zone; *C. valoniensis* also occurs in the succeeding basal *calliphyllum* ammonite zone (Yin *et al*., 2007: 714). On the basis that the *calliphyllum* zone is correlatable with the Planorbis Zone (see **13.1**), the stratigraphic occurrence of these bivalves in Tibet appears broadly comparable with that in England where, though recorded only from the Westbury Formation and Cotham Member (Lilstock Formation) at St Audrie's Bay (Fig. 6), *C. valoniensis* ranges into the Hettangian elsewhere (Ivimey-Cook *et al.*, 1999: 106), and *P. giganteum* occurs in the Langport Member and basal Blue Lias Formation, below a level equivalent to the base of the *calliphyllum* zone (Fig. 6).

6.1.3. Other macrofossil groups

Other macrofossil groups recorded from the succession at St Audrie's Bay and Doniford Bay include serpulids, solitary corals, gastropods, echinoderms and fish (Fig. 7). Gastropods are recorded only from the Blue Anchor and Westbury formations. A solitary coral (a montlivaltiid?) occurs in the Langport Member (Lilstock Formation). The echinoderms include an ophiuroid (*Aplocoma* sp.) from the Westbury Formation, and echinoid remains, mostly diademopsid spines, from the Langport Member and the Blue Lias Formation. Fish remains, mostly teeth, are commonest in the Blue Anchor and Westbury formations. They include representatives of the chondrichthyes (*Agkistracanthus*, *Hybodus*, *Lissodus*) and osteichthyes (*Gyrolepis*, '*Sargodon*').

6.2. Microfauna

6.2.1. Foraminifera

Copestake (1989) documented assemblages from the Mercia Mudstone Group to lower Lias Group (Planorbis Zone) succession in England and Wales, including that at St Audrie's Bay and Doniford Bay (Fig. 8). Occurrences in the Liasicus and Angulata zones in the eastern Bristol Channel region (Fig. 1A), including sections on the west Somerset coast at St Audrie's Bay and Watchet, were documented by Copestake and Johnson (1989).

Foraminifera from the Blue Anchor Formation, Westbury Formation and Cotham Member (Lilstock Formation) at St Audrie's Bay and the upper part of the Westbury Formation and the Cotham Member in Doniford Bay (Copestake, 1989, figs 5.4, 5.6) are dominantly agglutinating forms that comprise the *Glomospira*/*Glomospirella* Assemblage of Copestake (1989) (Figs 8, 13). *Glomospira subparvula* and *Dentalina pseudocommunis* appear, possibly in association with *Eoguttulina liassica*, in the Blue Anchor Formation. The first is also present in the Westbury Formation and ranges into, but not above, the Cotham Member; *D. pseudocommunis* was not recorded from those units but occurs in the upper Langport Member (Lilstock Formation) and in the Blue Lias Formation, up to a level in the Planorbis Subzone in west Somerset and higher elsewhere. *Ammodiscus auriculus*, *Bathysiphon* spp., *Glomospirella* sp. 1 and *Glomospira perlexa* appear in the lower part of the Westbury Formation and, with the exception of *B*. spp., range into, but not above, the Cotham Member in west Somerset where *B*. spp. range into the upper Langport Member. Elsewhere, *A. auriculus* ranges into the basal Blue Lias Formation. *Trochammina squamosa* appears near the top of the Westbury Formation and is present in the Cotham and Langport members. *Ammobaculites* cf. *eiseli* and *A*. sp. occur only in the Cotham Member in west Somerset, but elsewhere *A*. cf. *eiseli* also occurs in the Westbury Formation (Copestake, 1989, fig. 5.6).

Foraminifera from all but the highest part of the Langport Member in west Somerset comprise the *Eoguttulina liassica* Assemblage of Copestake (1989) (Figs 8, 13), in which *E. liassica* is abundant. In addition to taxa ranging upwards from the underlying beds (*Bathysiphon* spp., *Dentalina pseudocommunis*, *Trochammina squamosa*), this assemblage includes the first definite occurrence of *Eoguttulina liassica*. *Lingulina cernua* and *Reinholdella*? *planiconvexa* appear in the lower part of the Langport Member and, with *E.*

liassica, range upwards into the Blue Lias Formation; *Ammodiscus auriculus* is present at this level elsewhere (Copestake, 1989, fig. 5.6).

The first appearance of *Lingulina tenera collenoti*, in the highest part of the Langport Member, marks the base of the JF1 foraminifer zone of Copestake (1989) (Figs 8, 13). Elsewhere, *Lingulina tenera tenera* and *L. tenera* var. *octocosta* appear at the same level but in west Somerset these taxa appear in the basal Blue Lias Formation. *Dentalina pseudocommunis*, *Eoguttulina liassica*, *Lingulina cernua*, *Reinholdella*? *planiconvexa* and, elsewhere, *Ammodiscus auriculus* range upwards from the Langport Member into the Blue Lias Formation. *Reophax helvetica* was only recorded in the Langport Member in west Somerset but elsewhere appears earlier, in the Westbury Formation. *Vaginulina anomala* appears in the lowest beds of the Blue Lias Formation in west Somerset, but at the base of that unit elsewhere; it ranges into the Planorbis Subzone and *V. curva* appears in that subzone (Copestake, 1989, fig.5.6).

Marginulina/*Saracenaria hamus* and *Verneuilinoides* sp. appear at the base of the JF2 foraminifer zone of Copestake and Johnson (1989) (Figs 8, 13), at a level in the upper part of the Johnstoni Subzone in the Blue Lias Formation. Taxa that range up into the JF2 foraminifer zone include *Lingulina cernua*, *L. tenera collenoti*, *L. tenera tenera*, *Reinholdella*? *planiconvexa* and *Vaginulina curva*. *Nodosaria metensis* appears in the JF2 foraminifer zone in west Somerset where it is recorded up to the top of the Johnstoni Subzone (Copestake & Johnson, 1989, fig. 6.2.6); it is found at lower and higher levels in the Blue Lias Formation elsewhere. *Dentalina pseudocommunis*, *Eoguttulina liassica* and *Frondicularia* spp. occur in the JF2 foraminifer zone elsewhere (Copestake, 1989, fig. 5.6). *Lingulina tenera collenoti* and *Reinholdella*? *planiconvexa* range up to the top of the Liasicus Zone and into the Angulata Zone respectively in the eastern Bristol Channel region; elsewhere, *R.*? *planiconvexa* ranges to higher levels (Copestake & Johnson, 1989, fig. 6.2.6). In the eastern Bristol Channel region *Frondicularia brizaeformis* and *F. terquemi* subsp. *A* appear in the upper part of the Johnstoni Subzone, *Opthalmidium liasicum* in the Liasicus Zone, *Planularia inaequistriata* at the base of the Angulata Zone, and *Dentalina langi* and *Lingulina tenera substriata* in the upper part of that zone. Elsewhere, *Lingulina tenera substriata* appears lower in the Hettangian and, with *D. langi*, generally ranges only to the top of the Angulata Zone, and *O. liasicum* and *P. inaequistriata* appear at the base of the Liasicus Zone and range into the Sinemurian (Copestake & Johnson, 1989, fig. 6.2.6). *Frondicularia brizaeformis* ranges into the Liasicus Zone in the eastern Bristol Channel region but elsewhere, with *F. terquemi* subsp. A, it ranges above that zone (Copestake & Johnson, 1989, fig. 6.2.6).

Organic test linings of foraminifers occur in palynological residues from the Westbury Formation but are more common in the Cotham Member, above the erosion surface overlying the deformed beds, and also in the Langport Member; a few occur in the lower part of the Planorbis Zone (beds 17-29) in the Blue Lias Formation (Warrington, 1974, 1981, 1983, 1985, *in* Hounslow *et al*., 2004, fig. 5).

The candidate GSSP level lies within the JF1 foraminifer zone, c.6 m above its base (see **13.2**; Fig. 14). The LAD of *Lingulina tenera* var. *octocosta* (Fig. 8) is a close proxy for the candidate level; the LAD of *Vaginulina anomala* and FAD of *V. incurva* occur <4.6 m higher (see **13.2**; Fig. 14).

6.2.2. Ostracods

Ostracods from the Blue Anchor Formation to Blue Lias Formation (Angulata Zone) succession at St Audrie's Bay and Doniford Bay have been reported by Lord and Boomer (1990) (Fig. 9).

The Blue Anchor Formation ('Grey Marl') proved barren and the overlying Westbury Formation (*not* 'Watchet Beds') yielded only 'Cypridacea indet' (Lord & Boomer, 1990: 125; Appendix, 3). The succeeding Cotham Member ('Cotham Beds') yielded *Cytherelloidea* sp. and *Ogmoconchella aspinata*, and the Langport Member ('Langport Beds') only 'Cypridacea indet' (Lord & Boomer, *op. cit.*). In the Blue Lias Formation *Bairdia* sp., 'Cypridacea indet' and *O. aspinata* were recorded from the 'Planorbis Beds', 'Cypridacea indet', *O. aspinata*, *O.* sp., *Paradoxostoma pusillum* and *Polycope* sp. from the 'Liasicus Beds', and 'Cypridacea indet', *Ektyphocythere translucens*, *Nanacythere* sp., *O. aspinata*, *O. hagenowi* and *Polycope cerasia* from the 'Angulata Beds' (Lord & Boomer, 1990: 125; Appendix, 3, 4).

Additional taxa were reported from nearby sections to the west (Watchet) and east (Lilstock) (Figs 1B, 9). At Watchet, the 'Langport Beds' yielded *Cytherella* sp. and *Darwinula* sp.; ?*Ogmoconchella bristolensis* occurs both there and at Lilstock. At Watchet, the 'Watchet Beds' yielded *Isobythocypris* sp. and *Ektyphocythere translucens*; *Cytherella plattensis* and *Ektyphocythere* sp. were recorded from those beds at Lilstock (Lord & Boomer, 1990: 124, 126; Appendix, 2, 5). Most of the 'Watchet Beds' are now included in bed 1 of the Blue Lias Formation (Whittaker, 1978) (see ***5.2.2***). *Nanacythere* sp. was recorded from the 'Planorbis Beds' at Watchet (Lord & Boomer, 1990: 124; Appendix, 2).

An assemblage from the upper part of the Langport Member at Warren Bay [ST 05798 43311], c.1.5 km west of Watchet (Swift, 2003), is dominated by *Cytherella plattensis* and *Ogmoconchella bristolensis*, but includes new species of *Eucytherura* (*E. minor*, *E. sagitta*) and a form (*Cytherelloidea praepulchella*) previously identified as *Cytherelloidea pulchella* or *C.* cf. *pulchella* (Fig. 9).

The ostracods recorded by Lord and Boomer (1990) and Swift (2003) are indicative of the *Ogmoconchella aspinata* ostracod zone of Boomer (1991); this extends into the early Sinemurian (Fig. 13).

6.2.3. Conodonts

The Blue Anchor Formation and Langport Member at St Audrie's Bay (Swift, 1995a: 80) and the Langport Member near Watchet (Warrington, 1983: 132) have been examined for conodonts but proved barren. Conodonts have, however, been recovered nearby; from 0.15 m below the top of the Langport Member in a cliff at the east side of Lilstock Bay [ST 177 454], c.7.8 km east-north-east of the candidate Hettangian GSSP site (Swift, 1995a; 1995b, fig.3b) (Fig. 1B), and from the basal micrite bed in that member in a cliff in Warren Bay [ST 05798 43311], c.4.5 km west of that site (Swift, *pers. comm.* to GW, May 2003; see Swift, 2003, fig. 2a). Specimens from Lilstock include a dextral M element (Swift, 1995a, plate 6, fig. 2) assigned to *Chirodella verecunda*, and *Prioniodina*?, represented by a P element Type A (Swift, 1995a: 54). The Langport Member has also yielded Sc elements assigned to *C. verecunda* at unspecified localities in Somerset (Swift, 1995a: 52-53). Specimens from Warren Bay comprise small ramiform elements that are characteristic of assemblages from the Langport Member (Swift, *pers. comm.* to GW, May 2003).

Chirodella verecunda is the commonest conodont species recovered from the Langport Member (Swift, 1995a: 52-53; 1999a: 185). It occurs with *Prioniodina*? and *Misikella coniformis* in that member in Nottinghamshire (Swift, 1995a) where it is also recorded from the basal Lias Group (Swift, 1989, plate 37, fig. 3; 1995a: 65, plate 6, fig. 10; 1999a: 186), in association with *Misikella posthernsteini* (Swift, 1989, plate 37, fig. 1; 1995a: 65, plate 5, fig. 1). These specimens are unlikely to have been reworked from a missing, presumed eroded, Langport Member, though this possibility cannot be discounted (Swift, 1995a: 65). *Misikella posthernsteini* ranges from the *posthernsteini-bidentata* conodont interval zone (Norian, Late Triassic) to the highest conodont zone, the *ultima* range zone (Gallet *et al*., 2007, fig. 2).

Conodonts from the British Trias are almost colourless and have a CAI (condont alteration index) of <1, indicating that any heating experienced was low-level and related to depth of burial (Swift, 1995a: 59).

6.2.4. Other microfauna

No recovery of radiolarians has been reported from samples taken at St Audrie's Bay by Dr E. S. Carter in September 1997.

Holothurian sclerites have not yet been recorded from the St Audrie's Bay and Doniford Bay section. Elsewhere they are common in the Lilstock Formation, especially the Langport Member, but have not been reported from the Westbury Formation (Swift, 1999b: 167). Holothurian remains occur in the topmost Planorbis Zone and succeeding Hettangian beds, and in the lower Sinemurian in the Blue Lias Formation elsewhere in southwest England (Gilliland, 1992).

Scolecodonts occur in palynological residues from 0.31 m above the base of the Westbury Formation and 2.13 m above the base of the Lilstock Formation (Warrington, 1974, 1981, 1983, 1985).

6.3. Microflora

The palynology of the Branscombe Mudstone Formation (Mercia Mudstone Group) to lower Lias Group (Blue Lias Formation, bed 37) succession at St Audrie's Bay has been documented by Warrington (1974, 1979, 1981, 1983, 1985; *in* Warrington & Whittaker, 1984; *in* Hounslow *et al*., 2004). Fisher and Dunay (1981, fig. 1) recorded microfloras from 10 levels in the Cotham Member (Lilstock Formation) to Blue Lias Formation (top of the Planorbis Zone) succession. Van de Schootbrugge *et al.* (2007) documented assemblages from 20 levels in the Blue Lias Formation (beds 3 to 24), with emphasis on the organic-walled microplankton component.

6.3.1. Miospores

The lowest level at which spores and pollen were recovered at St Audrie's Bay is 14.02 m below the top of the Branscombe Mudstone Formation; samples from the underlying 49 m of that formation were barren or contained only reworked material (Warrington, 1979, 1983, 1985, *in* Hounslow *et al*., 2004, fig. 5). Miospores were recovered from only three levels in the upper part of the Branscombe Mudstone Formation and three in the lower part of the Blue Anchor Formation, but most samples from the upper 14.02 m of the latter formation, and from succeeding units, were productive (Fig. 10).

Circumpolles pollen, of cheirolepidacean conifer origin, are a background constituent of the terrestrial microfloras throughout the section studied. *Classopollis* spp. are prominent, in terms of relative abundance, in most assemblages, except those from the lower part of the Blue Lias Formation (below the upper part of bed 24), where they are subordinate to *Gliscopollis meyeriana*. The latter occurs in only small numbers below the erosion surface that overlies the deformed beds in the Cotham Member (see ***5.2.2***) whereas other circumpolles (*Granuloperculatipollis rudis* and *Geopollis zwolinskae*) only occur below that member (Fig. 10).

Taxa in associations from the Branscombe Mudstone Formation range upwards, through the Blue Anchor Formation, into the Penarth Group and, in some cases, the Blue Lias Formation. Progressive diversification occurs through the upper 9.75 m of the Blue Anchor Formation and the succeeding Penarth Group. A marked reduction in diversity occurs at the base of the Blue Lias Formation (Figs 10, 11). Only two spore genera and species are present in the two lowest associations from the Branscombe Mudstone Formation; associations from this formation consist largely of non-spore taxa, of which up to 10 genera occur in the two lowest associations and four in the highest. Associations from the bulk of the Rydon Member (Blue Anchor Formation) are similar in composition, with spores either absent or represented by only one or two genera, but with non-spore taxa represented by up to nine genera. Four spore genera and eight non-spore genera are represented in the highest association from the Rydon Member and four and five, respectively, in the lowest from the succeeding Williton Member. Spore genera present increase to six in the lower Westbury Formation, and from six to eight non-spore genera are present in that formation. Up to 11 spore genera and 11 non-spore genera are represented in the Cotham Member, below the erosion surface overlying the deformed beds; slightly smaller numbers, up to nine and seven respectively, are present in the member above that level. Four spore genera are represented at the base of the Langport Member (Lilstock Formation), and up to nine higher in that member; the numbers of non-spore genera range from four to seven. In Blue Lias Formation bed 1 only two spore genera and from three to six non-spore genera are represented, signalling a marked decrease in diversity. Spores are absent from most of the higher levels examined in the Blue Lias Formation (up to bed 37), with only one genus recorded from the top of bed 7 and two from the top of bed 24. Non-spore genera in this part of the succession range from one in bed 3, to from two to four at higher levels.

Circumpolles, mainly *Classopollis* spp. and *Granuloperculatipollis rudis*, dominate the lowest associations, from 14.02 and 13.61 m below the top of the Branscombe Mudstone Formation; *Gliscopollis meyeriana* and *Geopollis zwolinskae* occur in very small numbers. Other taxa present are the spore *Leptolepidites argentaeformis* and pollen (*Alisporites* spp., *Chasmatosporites* spp., *Ovalipollis pseudoalatus*, *Vesicaspora fuscus*); *Rhaetipollis germanicus* and a spore (*Acanthotriletes varius*) appear in the higher association (Figs 10, 12). Associations of similar character occur near the top of that formation and in the Rydon Member up to 9.75 m below the top of the Blue Anchor Formation, at which level the spore *Carnisporites spiniger* appears. At 7.01 m below the top of the Blue Anchor Formation the spores *Acanthotriletes ovalis*, *Carnisporites anteriscus*, *Deltoidospora* spp., the taeniate bisaccate pollen *Lunatisporites rhaeticus*, and definite specimens of the monosaccate pollen *Tsugaepollenites*? *pseudomassulae*, augment this association. Further diversification occurs in the Williton Member, with the appearance of *Ricciisporites tuberculatus* and the bryophyte spore *Porcellispora longdonensis* 1.6 m below the top of the member, and *Quadraeculina anellaeformis* 0.46 m below the top. *Ovalipollis pseudoalatus* becomes relatively more abundant in the Williton Member, and a peak abundance of *R. germanicus* occurs near the top of that unit (Fig. 10). A peak abundance of *O. pseudoalatus* occurs 0.31 m above the base of the Westbury Formation, which is also the highest occurrence of possible *Geopollis zwolinskae*; *Kraeuselisporites reissingeri* may appear at this level but is definitely present 0.76 m higher in the succession (Figs 10, 12). The relative abundance of *O. pseudoalatus* declines upwards through the Westbury Formation, but *R. tuberculatus* is most abundant 3.2 m above its base, where more spores (*Calamospora* spp.) appear (Fig. 10).

About 6.4 m of the Westbury Formation was not sampled at St Audrie's Bay, because of the condition of the cliff section when collecting was carried out. However, a complete record through the formation was obtained from the cored Selworthy 2 borehole at [SS 9244 4618], c.19 km west of the candidate GSSP site (Warrington *et al.*, 1995; Warrington *in* Edwards, 1999, fig. 28). The Selworthy record is compatible with that from St Audrie's Bay in terms of the composition of the assemblages and the relative abundances of taxa. At St Audrie's Bay, the highest definite occurrence of *Granuloperculatipollis rudis* is 0.31 m above the base of the Westbury Formation, though possible specimens may occur as high as 0.61 m below the top of that unit. At Selworthy this taxon occurs throughout the formation but is not found higher.

Diversification continues in the Cotham Member with the appearance, 0.23 m above its base, of the spores *Aratrisporites crassitectatus*, *Convolutispora microrugulata*, *Perinosporites thuringiacus*, *Retitriletes gracilis* and *Zebrasporites interscriptus*, and the pollen *Vitreisporites pallidus*. The last occurrence of *Lunatiporites rhaeticus* is at this level, and those of *Ovalipollis pseudoalatus* and *Tsugaepollenites*? *pseudomassulae* are 0.76 m above the base of the member (Fig. 12), immediately below the erosion surface overlying the deformed beds (see ***5.2.2***); *Camarozonosporites rudis* appears at this level. Similar associations, though without *O. pseudoalatus* and *T.*? *pseudomassulae*, occur in the upper part of the Cotham Member and in the Langport Member. *Perinopollenites elatoides* appears in the lower part of the Langport Member, followed by cf. *Neochomotriletes triangularis* and *Carnisporites leviornatus* higher in that member. A peak of abundance of *Kraeuselisporites reissingeri* occurs near the top of the member (Fig. 10), immediately below the 'Sun Bed' (see ***5.2.2***).

The character of the associations changes abruptly above the base of the Blue Lias Formation (Fig. 10). Particularly noticeable is the loss of many of the spore taxa present below that level, and the dominance of the circumpolles *Gliscopollis meyeriana* up to 8.97 m above the base of the formation, in bed 24 in the Planorbis Zone, with *Classopollis* spp. dominant above that level. Other taxa present in associations from the Blue Lias Formation include a few spores (*Calamospora* spp., *Deltoidospora* spp., *Kraeuselisporites reissingeri*) and pollen (*Alisporites* spp., *Chasmatosporites* spp., *Quadraeculina anellaeformis*); these are, with the exception of *K. reissingeri*, generally present in very small numbers. The highest definite records of *Rhaetipollis germanicus* and *Ricciisporites tuberculatus* are 2.6 m above the base of the Blue Lias Formation, in bed 5 (Figs 10, 12).

Orbell (1973: 17) placed a boundary between a lower (*Rhaetipollis*) and an upper (*Heliosporites*) miospore zone at the level of a 'rapid decline' in the numbers of *Ovalipollis pseudoalatus*, *Rhaetipollis germanicus* and *Ricciisporites tuberculatus* in the Cotham Member in successions in South Glamorgan, Oxfordshire and Nottinghamshire. However, the apparently synchronous 'rapid decline' of these pollen illustrated from those sections does not occur consistently in sections in Somerset and South Glamorgan, and others throughout central and eastern England. In these the decline is usually phased, with a reduction in the numbers of *R. germanicus* followed, in turn, by *O. pseudoalatus* and *R. tuberculatus*. These changes may all occur within the Cotham Member, though the decline in

R. germanicus may occur in the underlying Westbury Formation and that in *R. tuberculatus* at the top of the Cotham Member, or in higher beds (Warrington, 2005: 113). The '*Rhaetipollis*/*Heliosporites*' zone boundary is, therefore, less clearly defined than suggested by Orbell, and the utility of this concept is doubtful.

6.3.2. Organic-walled microplankton

The lowest level at which organic-walled microplankton were recovered at St Audrie's Bay is in the topmost Blue Anchor Formation; most samples from the succeeding Lilstock and Blue Lias formations were productive (Warrington, 1974, 1981, 1983, 1985, *in* Hounslow *et al*., 2004, fig. 5) (Fig. 10).

The lowest association, from 0.46 m below the top of the Williton Member, comprises a few dinoflagellate cysts (*Rhaetogonyaulax rhaetica*). The dinoflagellate cyst *Dapcodinium priscum* and an acanthomorph acritarch (*Micrhystridium* sp.) appear 0.31 m above the base of the Westbury Formation. Associations from higher in that formation and the lower 0.76 m of the Cotham Member (below the erosion surface overlying the deformed beds) comprise abundant *R. rhaetica*, sometimes with a few *D. priscum*, acanthomorph (*Micrhystridium* spp.) and herkomorph (*Cymatiosphaera polypartita*) acritarchs, and prasinophyte algae (*Tasmanites* spp.); *C. polypartita* occurs only in the lower Cotham Member. The abundance of *R. rhaetica* declines abruptly above the erosion surface in the Cotham Member, but this taxon ranges into the Blue Lias Formation, to bed 24 in the Planorbis Zone (Figs 10, 12). *Dapcodinium priscum* is most abundant in the Langport Member; it was definitely identified only up to 0.51 m above the base of Blue Lias Formation bed 1, but may be present 1.15 m higher, in bed 3. Acritarch associations from Blue Lias Formation are mostly dominated by acanthomorphs (*Micrhystridium* spp.) which have been recorded from the base of bed 1, and 2.6 and 4.63m above the base of the formation, in beds 5 and 7 respectively, and in the Planorbis Zone, 8.36 and 8.97 m (bed 24), and 12.86 m (bed 37) above the base of the formation. Polygonomorph (*Veryhachium* sp.) and netromorph (*Leiofusa jurassica*) acritarchs were recorded from bed 7, 4.63 m above the base of the formation. Prasinophyte algae (*Tasmanites* spp.) occur in beds 7, 24 and 37, 4.63, 8.36 and 12.86 m above the base of the formation respectively (Fig. 10).

Van de Schootbrugge *et al.* (2007, fig. 1, table 1) documented associations from 20 levels in the Blue Lias Formation (beds 3 to 24) at St Audrie's Bay, and identified a number of taxa, (marked * below) not recorded by Warrington (1981, *in* Hounslow *et al*., 2004, fig. 5) (Fig. 10). *Dapcodinium priscum* was recorded from beds 3 and 5 in the Blue Lias Formation, slightly higher than recorded by Warrington (*op. cit*.). The dinoflagellate cyst *Beaumontella langii** appears in bed 7 and is present in most samples from that level up to the base of bed 24 where it occurs with *B. caminuspina** (Fig. 12). Acritarch associations recorded by Van de Schootbrugge *et al.* (2007) are dominated by acanthomorphs (*Micrhystridium* spp.) but include *Baltisphaeridium* spp.* and small numbers of polygonomorphs (*Veryhachium*; six species), and netromorphs (*L. jurassica*, *Metaleiofusa diagonalis**). The acanthomorph population increases in diversity from one species at the base of bed 7, to eight at the top of that unit; up to five species occur in beds 9-11, and four at the top of beds 13-15 and in beds 17-19, but only one species is recorded from beds 20-22 and the base of bed 24. A solitary *Veryhachium* was recorded from bed 5, but the main occurrences of the polygonomorphs and netromorphs, in beds 7 to 11, correspond broadly with the distribution noted by Warrington (*op. cit*.). In addition to *Tamanites* spp., recorded from most sample levels in beds 3 to 24, Van de Schootbrugge *et al.* (2007, fig. 1, table 1) noted *Deunffia* sp.*, *Leiosphaeridia* spp.* and *Pleurozonaria wetzelii** in prasinophyte associations from beds 5, 7, and 9 to 16.

The presence of *Rhaetogonyaulax rhaetica* is indicative of the Rrh dinoflagellate cyst interval biozone of Powell (1992b) and Riding and Thomas (1992) who regarded its top, at the LAD of *R. rhaetica*, as marking the base of the Jurassic. The St Audrie's Bay occurrences show, however, that the top of this zone, as so defined, is c.3.6 m above the candidate Hettangian GSSP level. The succeeding beds are assigned to the *Dapcodium priscum* (Dpr) dinoflagellate cyst interval biozone of Powell (1992b) and Riding and Thomas (1992), which extends to the top of the Turneri Zone in the Sinemurian.

6.3.3. Calcareous nannoplankton

A coccolith ('*Annulithus arkelli*') was reported from the Westbury Formation in Doniford Bay, the Lilstock Formation in St Audrie's Bay and Doniford Bay, and the Blue Lias Formation (Liasicus and Angulata zones) at and immediately west of the candidate GSSP site (Hamilton, 1982, figs 3.3, 3.4). This taxon was the basis for the '*Annulithus arkelli* Zone', the lowest unit in a nannofossil zonation proposed for the British Mesozoic (Barnard & Hay, 1974) but 'specimens' are now considered to be of inorganic origin (Crux, 1987: 86, 96; Bown, 1998b: 31), and the lowest unit in that zonation is the *Schizosphaerella punctulata* Zone (JL1: Bown, 1987; NJ1: Bown *et al.*, 1988) (Fig. 13).

Hamilton (1982, figs 3.3, 3.4) recorded *Schizosphaerella punctulata* from the Cotham Member (Lilstock Formation) at St Audrie's Bay, and from the Blue Lias Formation (up to the Angulata Zone) at and immediately west of the candidate GSSP site. This taxon indicates the NJ1 nannofossil zone (Fig. 13) of Bown *et al.* (1988) and Bown and Cooper (1998: 36) who did not record *S. punctulata* below the Planorbis Zone. However, Van de Schootbrugge *et al.* (2007, fig. 1) record this taxon from bed 7 of the Blue Lias Formation at St Audrie's Bay (c.1 m below the candidate GSSP level; see ***13.2.2***, Fig. 14). With *Crucirhabdus primulus*, which appears c.2.2 m lower, at the start of the 'Main Isotope Excursion' of Hesselbo *et al* (2002) (see ***8.1.1***) (Van de Schootbrugge *et al.* (2007: 131), *S. punctulata* ranges up into the Planorbis Subzone.

7. MAGNETOSTRATIGRAPHY

Briden and Daniels (1999) detected three Normal and three Reversed polarity zones in the Mercia Mudstone Group between c.18 m above the base of the section and c.2 m above the base of the Blue Anchor Formation at St Audrie's Bay. Hounslow *et al.* (2004) documented the magnetostratigraphy of the St Audrie's Bay succession, from the base of the section, in the Branscombe Mudstone Formation, to bed 30 in the Blue Lias Formation (Planorbis Zone, Johnstoni Subzone) (Fig. 3); this work amplified and extended that of Briden and Daniels (*op. cit.*), and largely substantiated their results from the Mercia Mudstone Group.

Four Reversed and four Normal polarity units, and the lower part of a fifth, are recognised in the Mercia Mudstone Group (Hounslow *et al.*, 2004, fig. 2). In ascending order these are designated SA1r (>10.6 m), SA2n (c.8.2 m), SA2r (c.5.3 m), SA3n (c.23.7 m), SA3r (c.15.1 m), SA4n (c.4.6 m), SA4r (c.32.3 m) and SA5n (*pars*.); all but the last two occur in the Branscombe Mudstone Formation (Twyning Mudstone Formation *in* Hounslow *et al.*, 2004; see **5.1**). SA4r begins c.3.5 m below the top of that formation and extends to the top of the Rydon Member (Blue Anchor Formation); SA5n (c.15.8 m) begins at the base of the succeeding Williton Member and extends through the Penarth Group, into the lowest bed of the Blue Lias Formation.

A short Reversed interval (3n1r) was detected in the upper part of SA3n; short Normal intervals (3r1n, 3r2n) occur near the base and the top of SA3r, and short Reversed intervals (4n1r, 4n2r) in SA4n. A short Normal interval (4r1n) in SA4r occurs at the base of the Blue Anchor Formation. Uncertain polarity was recorded in SA1r and, over shorter intervals, in SA2n, SA3r, SA4n and SA4r.

Durations have been proposed for polarity units SA3n to SA4r (*pars*., below SA4r1n) by correlating the magnetostratigraphic record of the upper c.44 m of the Branscombe Mudstone Formation with an astronomical time scale based on ~100 ky eccentricity cycles (Kemp & Coe, 2007; see **11**)

Three short Reversed intervals were detected in SA5n (Hounslow *et al*., 2004, fig. 3); 5n1r and 5n2r occur in the lower part of the Westbury Formation and near the top of that formation respectively; 5n3r occurs at the base of the Cotham Member (Lilstock Formation). Uncertain polarity was recorded over a short interval spanning the Cotham Member – Langport Member boundary, and at the top of SA5n, in the lowest bed of the Blue Lias Formation (Fig. 3).

In the Blue Lias Formation, above SA5n, a very short Reversed polarity unit (SA5r; c.0.5 m) is followed by Normal polarity unit SA6n (Hounslow *et al*., 2004, fig. 3). SA5r occurs within the lowest bed of the Blue Lias Formation; SA6n begins c.0.25 m below the top of that bed and extends to the top of the section studied, in bed 30, in the basal part of the upper (Johnstoni) subzone of the Planorbis Zone. Levels with uncertain polarity occur in the lower part of SA6n, between the topmost bed 1 and the middle of bed 7, but principally in beds 4 and 6, and at the top of the section studied, in beds 23 to 30 (Fig. 3).

The Rydon Member – Williton Member boundary in the Blue Anchor Formation is a disconformity (see ***5.1.2***) and coincides with a change in polarity (from SA4r to SA5n); no polarity change was detected at similar features higher in the succession, such as the erosion surface above the deformed beds in the Cotham Member (Hounslow *et al*., 2004) (Fig. 3).

8. CHEMOSTRATIGRAPHY

8.1. Isotopes

8.1.1. Carbon

Hallam (1994) published δ^{13}C data from two samples from the Cotham Member, two from the Langport Member, and one from the ‘Watchet Member’ at St Audrie’s Bay; most of the last unit is now included in bed 1 of the Blue Lias Formation (Whittaker, 1978) (see ***5.2.2***). Results were also obtained from six levels between the top of the ‘Pre-planorbis Beds’ and 16.80 m higher in the Blue Lias Formation (Hallam, 1994: table 1).

Carbon isotope values ($\delta^{13}C_{org}$) from bulk organic matter from a much larger number of samples from St Audrie’s Bay have been reported by Hesselbo *et al*. (2002, fig. 4). Analyses were made on 127 samples (GSA Data Repository item 2002021) from a 28 m-section extending from the Williton Member (Blue Anchor Formation) to bed 43 or 44 in the Blue Lias Formation, at the base of the Liasicus Zone. Hesselbo *et al*. (2004a, fig. 4) documented the Total Organic Carbon (% TOC) and carbonate (% CARB) contents of part of this section, from the top of the Rydon Member (Blue Anchor Formation) to bed 29 in the Blue Lias Formation (Fig. 4).

In the Williton Member $\delta^{13}C_{org}$ values are between –26.21 and –27.75 ‰ PDB, rising to –25.38 near the top of that member and reaching –24.93 at the base of the succeeding Westbury Formation. Within that formation values range between –24.80 and –28.46; a series of minor negative excursions in the lower 6 m of the formation culminate in one that reaches from –28.46 to –28.36 at 5.2 and 5.6 m, respectively, above its base. Above this level values are <–27, rising to –24.80 and –24.88 at 7.4 and 7.6 m above the base of the formation, then falling to between –25.67 and –26.54. Values rise abruptly to –25.17 at the base of the Cotham Member (Lilstock Formation) and increase progressively to –24.46 at a level just above the erosion surface that overlies the deformed beds in that member. A prominent negative excursion (the 'Initial Isotope Excursion' of Hesselbo *et al*., 2002) commences at that level and within <0.3 m reaches –29.30, at around the Cotham Member – Langport Member boundary in the Lilstock Formation. A value of –28.94 in the basal Langport Member is followed upwards in that member by others between –26.54 and –27.25. A negative excursion, to –28.35, occurs at the base of Blue Lias Formation bed 1, above which values rise progressively to –25.60 at the top of this bed. Above this level a broad negative trend occurs, reaching –29.53 in bed 7, above which values generally rise, to –28.40 in bed 12. Hesselbo *et al*. (2002) identify the start of a 'Main Isotope Excursion' in bed 6. Rapid fluctuations occur above bed 12, with strong negative excursions to –29.95 in bed 13 (just above the candidate GSSP level), –30.03 in bed 17, and –30.23 in the middle of bed 24. Above that level values generally rise, to –26.91 in bed 27 (near the boundary between the Planorbis and Johnstoni subzones) above which a further broad negative trend occurs, reaching –29.43 in bed 36. Values again generally rise, to –27.36 in beds 40-42 at the top of the Planorbis Zone, above which a further negative trend is indicated, with values moving to –29.08 at the top of the section studied, in bed 43 or 44 in the basal Liasicus Zone.

The % TOC record from the topmost Rydon Member to the Blue Lias Formation (bed 29), corresponding to part of the above section (Hesselbo *et al*., 2004a, fig. 4), shows levels of generally <2% in the succession below the Blue Lias Formation; a peak of c.8% occurs in the middle of the Westbury Formation (bed 12 of Richardson, 1911: 23). No corresponding change in the % TOC occurs at the level of the $\delta^{13}C_{org}$ Initial Isotope Excursion. Within the Blue Lias Formation rapid fluctuations between trace levels and 10% occur, with a peak of 12% in bed 13 (Fig. 4).

The % CARB record from the topmost Rydon Member to bed 29 in the Blue Lias Formation (Hesselbo *et al*., 2004a, fig. 4) (Fig. 4) shows levels generally >20% in the Blue Anchor Formation, with a maximum of >80% at the Rydon Member – Williton Member boundary. In the Westbury Formation, % CARB peaks of up to 80% are associated with thin limestone beds but at other levels the % CARB is <10%. An abrupt increase in % CARB occurs at the base of the Cotham Member, with values reaching 80% just below the erosion surface above the deformed beds in that member. An abrupt decrease occurs in the higher part of that member, with values of c.30% at a level that broadly corresponds to the $\delta^{13}C_{org}$ Initial Isotope Excursion. Levels of between 30 and 90% CARB occur in the Langport Member but these drop to c.30% at the base of the Blue Lias Formation, from where they rise to >90% in bed 4. Rapid fluctuations in % CARB occur in beds 5 to 22, with c.20% present at the level of the TOC peak and $\delta^{13}C_{org}$ negative excursion in bed 13. The % CARB varies between 30 and 50% in much of the upper part of the Planorbis Subzone (bed 24) but reaches 80% in the highest part of that subzone.

A study of $\delta^{13}C$ from the bivalve *Liostrea hisingeri* from Blue Lias Formation beds 6, 7 and 16 at St Audrie's Bay showed levels of up to 4 ‰ PDB in bed 6 and at the base of 7. The level declines progressively to almost 1.5 near the top of bed 7 and increases to around 2 in bed 16 (Van de Schootbrugge *et al.*, 2007, fig. 3).

8.1.2. Strontium

Strontium isotope ($^{87}Sr/^{86}Sr$) ratios from 15 levels in the Lilstock and Blue Lias formations at St Audrie's Bay were reported by Hallam (1994, table 1). The $^{87}Sr/^{86}Sr$ values show several marked excursions (Hallam, 1994, fig. 2) but these are, unfortunately, influenced by diagenesis and cannot be used for stratigraphic correlation (Hallam, 1994: 1082).

8.1.3. Oxygen

Leslie *et al.* (1993, fig. 7b) published $\delta^{18}O$ data from the upper part of the Branscombe Mudstone Formation and the basal Blue Anchor Formation at St Audrie's Bay. However, these authors give a thickness of >140 m for the exposed Branscombe Mudstone Formation, in contrast to the c.67 m documented by Whittaker and Green (1983: 47-48), and the plot of their results may be distorted. The $\delta^{18}O_{PDB}$ values from this formation generally ranged between –1 and c.–5.5, with one excursion to c.1.2 that was interpreted as reflecting a brief period of increased evaporation. At and immediately above the base of the Blue Anchor Formation values reached c.1.5 before returning to >–2.

Hallam (1994, table 1) published $\delta^{18}O$ data from 11 of the levels in the Lilstock and Blue Lias formations at St Audrie's Bay that had also been analysed for $^{87}Sr/^{86}Sr$ (see ***8.1.2***). Unfortunately, the Sr isotope compositions had been influenced by diagenesis (Hallam, 1994: 1082), and the $\delta^{18}O_{PDB}$ values will have been similarly affected and cannot therefore be used for stratigraphic correlation.

A study of $\delta^{18}O_{PDB}$ from the bivalve *Liostrea hisingeri* from Blue Lias Formation beds 6, 7 and 16 at St Audrie's Bay showed levels around –0.75 ‰ in bed 6. The level rises to nearly 0 in the middle of bed 7, falls to c.-2.4 near the top of that bed and rises to c.–1.25 in bed 16 (Van de Schootbrugge *et al.*, 2007, fig. 3).

8.1.4. Rhenium-Osmium

Abundances of Re and Os in the Westbury and Blue Lias formations in west Somerset (St Audrie's Bay and Watchet) and South Wales (Lavernock) (Fig. 1A) have been documented and presented in relation to the St Audrie's Bay section (Cohen & Coe, 2002, fig. 2). Results from samples from St Audrie's Bay (below) are from GSA Data Repository item 2002024; Re, Os and ^{192}Os abundances, and $^{187}Os/^{188}Os$ ratios, are from Westbury Formation beds 12 and 8 of Richardson (1911) and Blue Lias Formation beds 1, 5 and 14 of Whittaker and Green (1983). Marked increases in Re, Os and ^{192}Os abundances occur between Westbury Formation bed 8 and Blue Lias Formation bed 1, and between Blue Lias Formation beds 5 and 14.

Formation	**Bed**	Re (ppb)	Os (ppb)	^{192}Os (ppb)	$^{187}Os/^{188}Os$
Blue Lias	14	87.4	2.0037	0.7478	0.848
	5	18.438	1.1096	0.4328	0.491
	1	16.729	0.18	0.0594	1.926
Westbury	8	1.066	0.0854	0.032	0.808

12	0.736	0.1356	0.0506	0.842

The compilation presented by Cohen and Coe (2002, fig. 2) includes results from four additional samples from the Westbury Formation at Watchet and 11 from the Blue Lias Formation at Lavernock, and reflects the trends evident in the results from St Audrie's Bay. High levels of ^{192}Os are reached slightly lower in the succession than those in Re but both show an abrupt increase in bed 14 at St Audrie's Bay. Data from the Lavernock section (GSA Data Repository item 2002024) show that the abundance of Os decreases progressively through the Planorbis Subzone and to around the middle of the Johnstoni Subzone whereas that of Re remains high (>86 ppb) in the Planorbis Subzone and the lower Johnstoni Subzone but decreases to 72.08 ppb around the middle of that subzone.

8.2. Other (elemental) geochemistry

8.2.1. Magnesium/Calcium

A study of Mg/Ca from bivalve (*Liostrea hisingeri*) calcite from Blue Lias Formation beds 6, 7 and 16 at St Audrie's Bay showed levels of between 7 and 8 mmol/mol^{-1} in bed 6 and most of bed 7. The level rises to almost 10 near the top of bed 7 and falls to around 4 in bed 16 (Van de Schootbrugge *et al.*, 2007, fig. 3).

8.2.2. Strontium/Calcium

A study of Sr/Ca from bivalve (*Liostrea hisingeri*) calcite from Blue Lias Formation beds 6, 7 and 16 at St Audrie's Bay showed a level of 0.55 mmol/mol^{-1} in bed 6. The level rises to >0.6 in the basal part of bed 7, falls to <0.55 in the middle of that bed, then rises to c.0.65 near its top and falls to nearly 0.55 in bed 16 (Van de Schootbrugge *et al.*, 2007, fig. 3).

Van de Schootbrugge *et al.* (2007) also provided data on Mn/Ca, Fe/Ca and Al/Ca from *Liostrea hisingeri* from Blue Lias Formation beds 6, 7 and 16 at St Audrie's Bay (*ibid*., Table 2).

8.2.3. Thorium/Uranium

Wignall measured Th/U ratios in the upper Penarth Group and the lowest beds of the Blue Lias Formation at St Audrie's Bay (Wignall, *in* Hallam, 1995, fig. 2). In the figure caption, 0.35 m of limestone shown at the base of a graphic lithological log of the section studied is stated to be 'limestone of the Langport Member', implying that the overlying beds are the Blue Lias Formation. This is incorrect; the section illustrated is directly comparable, apart from this limestone, with that recorded by Whittaker and Green (1983, figs 12, 13), from the deformed beds in the Cotham Member (Lilstock Formation) up to bed 5 in the Blue Lias Formation. According to this reinterpretation of the section, Th/U ratios were measured at two levels in the Cotham Member (above the deformed beds), four in the Langport Member (Lilstock Formation), four in Blue Lias Formation bed 1, and one each in beds 2, 4 and 5 in that formation. Ratios in the Cotham Member and much of the Langport Member are around 1, but c.2.5 was recorded near the top of the latter unit. In Blue Lias Formation beds 1 and 2 the ratios are between 1 and 2; ratios of 3 and between 2 and 3 were recorded from beds 4 and 5 respectively. These results were interpreted as reflecting anoxic to dysoxic conditions at and close above the seabed (Hallam, 1995: 251).

9. CLAY MINERALOGY

Leslie *et al*. (1993, fig. 6b) documented the clay mineralogy of the Branscombe Mudstone Formation and the basal Blue Anchor Formation at St Audrie's Bay. However, these authors give a thickness of >140 m for the exposed Branscombe Mudstone Formation, in contrast to the c.67 m recorded by Whittaker and Green (1983: 47-48), and the plot of their results from that formation may be distorted. Mayall (1979, fig. 3; 1981, fig. 4) documented the clay mineralogy of the Blue Anchor Formation and (1979, fig. 3), the Penarth Group and basal Blue Lias Formation, and Deconinck *et al.* (2003) that from the Blue Lias Formation (to the top of the Liasicus Zone) at St Audrie's Bay, and to higher levels in that formation at localities farther east on the Somerset coast.

The lowest clay mineral assemblage from the Branscombe Mudstone Formation comprises illite (70%), chlorite (10%) and mixed-layer chlorite/smectite (20%). The illite content increases to 85-95% in the upper part of the formation where from 1 to 5% of both chlorite and mixed-layer chlorite/smectite are also present. Smectite (up to 5%) occurs at four levels, and small amounts (<2%) of palygorskite/sepiolite were recorded at seven levels, mostly in the lower part of the section (Leslie *et al*., 1993, fig. 6b).

Clay mineral assemblages from the Blue Anchor Formation are also dominated by illite. Leslie *et al*. (1993, fig. 6b) recorded >90% in the lowest 10 m of the formation, together with small amounts of chlorite and and sporadic traces of mixed-layer chlorite/smectite. Mayall (1979, fig. 3; 1981, fig. 4) recorded 50-80% illite in the lower c.15 m of this formation, with 60-80% present at higher levels, and 90% at c.2 m below the top of the Rydon Member. The illite content declines to 80% at the top of that member and to c.70% in the succeeding Williton Member. Also present in the Blue Anchor Formation are illite-smectite (c.5-25%), chlorite (c.2-5%) and corrensite. The corrensite content is up to 10% in the lower c.6 m of the Rydon Member, and generally >10% between that level and c.12 m below the top of the member, with peaks of c.25%, >30% and c.20% around 27, 20 and 17 m below that level respectively. Between c.12 and 3 m below the top of the member the corrensite content is c.5%; it is not recorded from the topmost beds, or from the Williton Member, assemblages from which comprise illite (c.65-75%), illite-smectite (20-30%), and up to 5% chlorite (Mayall, 1979, fig. 3; 1981, fig. 4). An incomplete record from the Westbury Formation (Mayall, 1979, fig. 3) shows the presence of illite (c.40-95%), illite-smectite (c.20-55%), c.5% chlorite, and small amounts of vermiculite. Assemblages from the Lilstock Formation are similar, but lack vermiculite. Those from the lowest beds in the Blue Lias Formation include kaolinite, in addition to illite (c.50-60%), illite-smectite (c.25-35%) and chlorite (c.5%); the kaolinite content is c.5% at the base of this formation, but increases to c.15% at c.3 m above that level (Mayall, 1979, fig. 3). Assemblages from the Blue Lias Formation (up to the top of the Liasicus Zone) at St Audrie's Bay (Deconinck *et al*., 2003, fig. 3) are dominated by illite (c.40-60%) and illite-smectite (c.20-30%), but include kaolinite (c.10-30%) and chlorite (c.10-15%). A slight decrease in the illite content begins around bed 13 and continues to around the top of the Portlocki Subzone, (Liasicus Zone); kaolinite shows a slight but generally progressive increase through the same interval. Kaolinite/illite ratios show prominent peaks at the base of bed 13, the top of the Planorbis Subzone, and around the top of the Portlocki Subzone (Deconinck *et al*., 2003, figs 3, 4). There is no indication of significant burial or thermal diagenesis of the sediments; an estimated average T_{max} indicates a maturation level below the oil window (Deconinck *et al*., 2003: 261-262, fig. 7).

10. SEQUENCE STRATIGRAPHY

A sequence stratigraphic interpretation of the Mercia Mudstone Group to Lias Group succession at St Audrie's Bay has been given by Hesselbo *et al*. (2004a; fig. 4) (Fig. 4). Following a fluctuating rise in sea level during deposition of the upper part of the Blue Anchor Formation (Williton Member), the Westbury Formation represented a Transgressive Systems Tract (TST). This was terminated by Falling Stage and Lowstand Systems Tracts during deposition of the lower part of the Cotham Member (Lilstock Formation), with a Sequence Boundary marked by the erosion surface overlying the deformed unit in that member (see ***5.2.2***). A TST returned through the upper part of the Penarth Group and into the Blue Lias Formation. Wignall *et al*. (2007: 399) interpreted the emergence or erosion surface in the Cotham Member as an amalgamated sequence boundary and flooding surface. Hesselbo *et al*. (2004b) disputed the claim (Hallam & Wignall, 2004, repeated by Wignall *et al.* 2007) that another rapid regressive-transgressive event occurred at the Lilstock Formation – Blue Lias Formation boundary (see ***5.2.2***).

The St Audrie's to Doniford Bay cliff section includes beds up to the Angulata Zone but beds as high the Bucklandi Zone (lower Sinemurian) are present on the foreshore (Whittaker & Green, 1983: 63-68, fig. 13). Medium-scale (Third Order) surfaces, comprising a possible maximum flooding surface in the middle of the Liasicus Zone and a possible sequence boundary in the middle of the Angulata Zone, may occur in this succession (Hesselbo & Jenkyns, 1998: 572, fig. 11).

11. CYCLOSTRATIGRAPHY

Kemp and Coe (2007) recognised ~100 ky eccentricity cycles in the upper c.44 m of the Branscombe Mudstone Formation (Mercia Mudstone Group) exposed in St Audrie's Bay. These were used to construct an astronomical time scale for c.3.6 my of the Late Triassic and, by correlation with the magnetostratigraphic record from the same section (Hounslow *et al*., 2004), to propose an astronomically calibrated record of geomagnetic polarity from which the durations for the following polarity units were derived (Kemp & Coe, 2007, fig. 4):

Polarity unit	**Duration (ky)**	
SA4r (*pars*., below SA4r1n)	270.69	+ 4.72 / – 4.69
SA4n	388.44	+ 11.56 / – 11.67
SA3r.2r	1297.36	+ 31.23 / – 29.41
SA3n2n	371.87	+ 124.68 / – 122.18
SA3n1r	170.15	+ 161.26 / – 170.15
SA3n1n	1101.59	+ 121.26 / – 97.42

Unfortunately, no cyclostratigraphic work has been reported from higher formations in the St Audrie's Bay and Doniford Bay section, so that no estimates can be given for the durations of polarity units SA5 (which extends to just below the candidate GSSP level) or SA6 (which extends into the Hettangian).

However, the results of a study of the Lilstock Formation (Penarth Group) and the Blue Lias Formation (up to the early Sinemurian Semicostatum Zone) to the west of Lyme Regis, Dorset, south-west England (Weedon *et al*., 1999) [c.SY 33 91] are relevant to the west Somerset section. The Blue Lias Formation at Lyme Regis shows evidence of regular sedimentary cyclicity linked to Milankovitch cycles but modulated by long-term (million year) variations in sedimentation rate; 20ka precession, 38ka obliquity (dominant) and 95ka eccentricity cycles were detected and the following minimum durations for ammonite zones and subzones proposed (zonal and subzonal orthography of Weedon *et al*., 1999, table 1):

Stage (duration: my)		**Zone (duration: ka)**		**Subzone (duration: ka)**	
Sinemurian (*pars*.)		*bucklandi*	342	*bucklandi*	76
				rotiforme	76
				conybeari	190
Hettangian	1.29	*angulata*	456	*complanata*	380
				extranodosa	76
		liasicus	494	*laqueus*	228
				portlocki	266
		planorbis	342	*johnstoni*	152
				planorbis	190

These values provide a minimum time-scale for the succession above the candidate GSSP level in west Somerset, and minimum time-constraints on the rates of processes in that succession. The subzonal division of the Bucklandi Zone follows Dean *et al*. (1961). It differs from that used by Ivimey-Cook and Donovan (1983), in which only the Conybeari and Rotiforme subzones are recognised in that zone, and that of Page (2005) in which the zone comprises the Conybeari, Rotiforme and Depressa subzones (Fig. 13).

Taken together these results provide an indication of the precision with which the events around the candidate GSSP level can be dated in this area.

12. GAMMA-RAY LOG CHARACTER

The Burton Row Borehole [ST 3356 5208], c.25 km east-north-east of the candidate GSSP (Fig. 1A), proved a succession from the Lias Group (late Pliensbachian, Margaritatus Zone), through the Penarth and Mercia Mudstone groups to older Triassic and possible Permian formations (Whittaker & Green, 1983: 121-123). It was fully cored and logged geophysically (Penn, 1987, table 1), and is the nearest section to the candidate GSSP that has those attributes.

A gamma-ray log has been made from measurements on the outcrop of the Branscombe Mudstone and Blue Anchor formations at St Audrie's Bay and correlated with that from the Burton Row Borehole (Leslie *et al*., 1993, fig. 5). However, these authors (*ibid*. figs 6b, 7b) give a thickness of >140 m for the exposed Branscombe Mudstone Formation, in contrast to the c.67 m recorded by Whittaker and Green (1983: 47-48), and the plot of their results may be distorted.

Bessa and Hesselbo (1997, fig. 3) defined six units (BL1–BL6) in a gamma-ray log of the Blue Lias Formation (up to the Bucklandi Zone, early Sinemurian) exposed in the St Audrie's Bay to Doniford Bay section. Unit BL1 extends to the top of the Planorbis Zone, and BL2 spans the Liasicus Zone. Four smaller-scale cycles are recognised in BL1 and five in BL2; these cycles are thinner than the subzones in the Planorbis and Liasicus zones and offer higher stratigraphic resolution, with the possibility of detecting minor hiatuses. One such hiatus, that is below resolution by biostratigraphy, is inferred between the Planorbis and Liasicus zones in the candidate GSSP section; correlation of gamma-ray logs indicates that the topmost c.2.5 m of beds in the Planorbis Zone at St Mary's Well Bay [ST 176 677 to ST 187 681], near Lavernock (Fig. 1A), South Glamorgan, Wales, have no equivalents in the candidate GSSP section, c.25 km to the south-south-west in Somerset (Bessa & Hesselbo, 1997: 116, fig. 5). The magnitude of this inferred hiatus is constrained by the minimum duration (152 ka) suggested for the Johnstoni Subzone (see **11**). Bessa and Hesselbo (1997, fig. 9) also proposed a correlation of the gamma-ray log from the St Audrie's Bay to Doniford Bay section with that from the Burton Row Borehole.

13. CORRELATION

The ability to correlate from a candidate GSSP to other successions is paramount and must be demonstrated before the criterion for identifying the boundary is incorporated in a definition. A biostratigraphical criterion is generally preferred as non-biostratigraphic events (e.g. magneto- or chemostratigraphic), though potentially affording higher resolution, are repetitive and require calibration by biostratigraphic or isotopic dating (Remane *et al.*, 1996: **2.3**, 78, 79).

The level advocated for the base of the Hettangian in this proposal is the appearance, in relative abundance, of the ammonite *Psiloceras planorbis* at the base of Blue Lias Formation bed 13 of Whittaker and Green (1983), below which ammonites, comprising other psiloceratids, are scarce. This event marks the base of the Planorbis Subzone and the *planorbis* biohorizon. No causal relationship to processes such as volcanism or gas hydrate dissociation (e.g. Pálfy *et al.*, 2001; Hesselbo *et al.*, 2002) is suggested or implied. Such relationships may, however, exist in the case of the chemostratigraphic proxies (see ***13.2.1***) noted in Blue Lias Formation beds 13-15, the base of which is the boundary level advocated in this GSSP proposal. This level is proposed for the following reasons:

1. It is the level at which *Psiloceras planorbis* appears within a succession of psiloceratids that is widely recognised and correlatable to other marine successions (see **13.1**).
2. There are chemo-, magneto- and biostratigraphic proxies that approximate very closely (within 1m) to, or are near, this level that may be used to overcome provincialism in the ammonite faunas and to correlate to other marine and to non-marine successions (see **13.2**).
3. The level corresponds with the base of the lowest classical Standard (ammonite) Zone (Chronozone) and Subzone (Subchronozone) of the Hettangian Stage.

13.1. Correlation of the ammonite succession

The succession of ammonites demonstrated in Blue Lias Formation beds 8 to 24 at St Audrie's Bay and Doniford Bay (see ***6.1.1***; Fig. 5) has also been recognised at the following widely separated sites in the UK:

a) In the cored Wilkesley Borehole, Cheshire (Bloos & Page, 1997a, b; Bloos, 2004), c.205 km north-north-east of St Audrie's Bay.
b) In a cored borehole at Staithes, North Yorkshire (Page*, in prep.*, and *pers. comm.* to GW, April 1998), c.410 km north-north-east of St Audrie's Bay.
c) In outcrops at Waterloo Bay, Larne, Northern Ireland (Simms & Jeram, 2006), c.475 km north-north-west of St Audrie's Bay.

The FAD of definite *Psiloceras planorbis* is proposed as marking the base of the Planorbis Subzone in the candidate GSSP because this level is identified *within* a succession of psiloceratid ammonites that is now recognised over a large geographical area (see above). This obviates objections (e.g. Hallam, 1990: 422) to the earlier proposal utilising the FAD of *Psiloceras*, below which no ammonites, other than a psiloceratid reported from the topmost bed of the Westbury Formation (Penarth Group) (see ***6.1.1***), are known from Mesozoic successions in the UK.

The earliest ammonite fauna in the North West European Province characterizes the Planorbis Subzone (Bloos, 2004), or Planorbis Subchronozone, to which Page and Bloos (1998) and Page (2005) assigned the *erugatum*, *imitans*, *antecedens*, *planorbis*, *sampsoni* and *plicatulum* biohorizons. This succession is c.5.3 m thick in west Somerset but is thicker elsewhere, e.g. c.13.8 m in the Wilkesley Borehole, Cheshire (Bloos & Page, 1997a, b).

The St Audrie's Bay candidate GSSP proposal limits the subchronozone to the *planorbis*, *sampsoni* and *plicatulum* biohorizons, with the *erugatum*, *imitans* and *antecedens* biohorizons becoming, by definition, pre-Hettangian. The *erugatum*, *imitans* and *antecedens* biohorizons are <0.5 m thick in the candidate GSSP section and may be relatively condensed there, compared with, for example, Cheshire where they are c.10.2 m thick (Page, 2005: 16). Conversely, the *planorbis*, *sampsoni* and *plicatulum* biohorizons in Somerset are thicker (c.4.8 m) than in Cheshire (c.3.6 m), and the lowest Hettangian subchronozone, as advocated here, is not, therefore, relatively condensed in the candidate GSSP section.

Provincialism is ubiquitous in psiloceratid faunas. In the North West European Province, outside the UK, these usually begin with *Psiloceras psilonotum*, typically associated with *P. plicatulum*. In the Mediterranean Province the earliest fauna characterizes the *Psiloceras calliphyllum* zone; records of *P. planorbis* and *P. psilonotum* from the Alps are erroneous (Bloos, 2004). However, Bloos (*op. cit.*) concluded that the bases of the *planorbis* and *calliphyllum* zones are correlatable, thus admitting correlation of a level at or close to that proposed in the St Audrie's Bay candidate GSSP section with one in Mediterranean Province successions. This view is supported by comparison of the levels of the appearance of *P. planorbis* and *P. calliphyllum* in relation to carbon isotope profiles from, respectively, St Audrie's Bay and the Tiefengraben, Austria (Kuerschner *et al.*, 2007, fig. 9). The first $\delta^{13}C_{org}$ excursion to c.–30 in the 'Main Isotope Excursion' of Hesselbo *et al.* (2002, fig. 2) approximates very closely to the appearance of *P. planorbis* at St Audrie's Bay (see ***13.2.1***.a; Fig. 14). In the Tiefengraben the correlative sequence is thicker but *P. calliphyllum* appears at the level of a similar excursion.

Recognition of the *calliphyllum* zone in the Tibetan Himalayas (Yin, 2007; Yin *et al.*, 2007), and a record of a psiloceratid assigned to *Psiloceras planorbis* from the Ladakh Himalaya (Krishna *et al.*, 1997), considerably extend the geographical range of correlation of this level. Yin *et al.* (2007) proposed a new local zone (*tibeticum*) between the *marshi* and *calliphyllum* zones in sections at Germig, Tibet, and tentatively regarded it as the lowest Jurassic zone in the Himalayas. The base of this zone is marked by the appearance of *Neophyllites* sp. and *Choristoceras nyalamense*, above the range of *C. marshi*; *Psiloceras tibeticum* appears higher in the zone. *Neophyllites* cf. *biptychus* and *Nevadaphyllites* cf. *psilomorphus*, followed by *P. calliphyllum*, appear in the *calliphyllum* zone; *Nevadaphyllites psilomorphus* is also known from that zone in the Alps. The stratigraphic relationships of *Neophyllites* and *P. calliphyllum* at Germig are analogous to those of *Neophyllites* and *P. planorbis* in the St

Audrie's Bay candidate GSSP section, and consistent with the conclusion (Bloos, 2004) that the bases of the *planorbis* and *calliphyllum* zones are correlatable. This relationship was also recognised by Guex *et al.* (2004, fig. 4, 2006, fig. 1) and Yin *et al.* (2007, Table 2) who, however, advocated levels lower in the ammonite succession for the base of the Hettangian. Guex *et al.* (2004, 2006) and others, for example Lucas *et al.* (2007) and Hillebrandt and Krystyn (2007, consider the appearance of *Psiloceras spelae* and *P. tilmanni*, *within* the range of *Choristoceras* spp., preferable for marking the base of that stage. However, Longridge *et al.* (2007: 155) have drawn attention to difficulties with this approach.

A similar faunal succession was thought to occur in northeastern Russia where *Psiloceras planorbis* was recorded above the *Primapsiloceras primulum* zone, the lowest Jurassic ammonite zone in that region (Polubotko & Repin, 1981). Dagys (2000) reviewed the relevant material and rejected both the presence of *Psiloceras planorbis* and the concept of the *primulum* zone as the oldest Jurassic zone, on the basis that the index fossil indicated an horizon comparable with that of species of *Psiloceras* such as *P. primacostatum*, rather than the earlier *P. planorbis* and *P. tilmanni*. Guex *et al.* (2006, fig. 1) considered that '*Primapsiloceras primulum*', as *Kammerkarites primulus*, occurs above a level equivalent to that of *Psiloceras rectocostatum* and, in northeast Russia, above a substantial gap in the ammonite succession that spans levels including equivalents of the *marshi* and *calliphyllum* zones.

At St Audrie's Bay the appearance of numerous smooth psiloceratid ammonites corresponds with the proposed GSSP horizon, below which psiloceratids are scarce and above which *Psiloceras planorbis* is common (e.g. Fig. 2g). Guex *et al.* (2004: 33) regarded the "*explosion and worldwide distribution of abundant smooth Psiloceras……as a more or less penecontemporaneous evolutionary event representing a good proxy for large-scale correlation of the typical planorbis-psilonotum beds*", with indirect confirmation being given by its association with a second negative carbon isotope excursion, as seen in beds with *P. planorbis* at St Audrie's Bay (see ***13.2.1.***a). Wignall (*in* Wignall *et al.*, 2007: 386) considered a level marked by the sudden appearance of large numbers of psiloceratid ammonites to be "*one of the most distinctive and instantly recognisable features of Triassic-Jurassic boundary successions throughout the world*" and that this would be a "*more utilitarian (and reliable) T-J boundary*" than one based on the FAD of the genus *Psiloceras*. In Nevada, U.S.A., this event is represented by the first occurrence of abundant *Psiloceras pacificum*, above the ranges of *Choristoceras*, cf. *Neophyllites* and earlier *Psiloceras*, including *P. tilmanni* (Guex *et al.*, 2004, fig. 1; Lucas *et al.*, 2007, figs 7, 16), and is thus in a stratigraphic relationship comparable with those seen in Tibet and the St Audrie's Bay candidate GSSP section.

Within ammonite successions known from Triassic-Jurassic boundary sequences, the level of appearance of abundant smooth *Psiloceras*, represented by *P. planorbis* in England, *P. calliphyllum* in the Alps and Tibet, and *P. pacificum* in the U.S.A., above the range of *Choristoceras* spp. and the appearance of *Neophyllites* spp., has optimal potential for wide correlation (*vide* Guex *et al.*, 2004: 33; Wignall *et al.*, 2007: 386), and is supported by an extensive range of proxies (see **13.2**).

13.2. Proxies

The following proxies provide means of correlating from the candidate GSSP to marine successions in other faunal (ammonite) provinces, or that lack ammonites, and to non-marine successions. They include ones that approximate very closely (within 1 m) to the candidate

GSSP level and others that offer broader correlation with levels between 7 m below that horizon, but above a sequence boundary (see ***5.2.2***, ***6.1.2***, **10**), and 8 m above the candidate level (Fig. 14). Palynomorphs, calcareous nannoplankton, foraminifers, ammonites and conodonts provide proxies, but bivalve taxa provide only broad characterisation of the GSSP level and are not proposed as proxies (see ***6.1.2***). Non-biostratigraphic proxies are provided by features in the magneto- and chemostratigraphic records.

13.2.1. Approximating to the candidate GSSP level (within 1 m)

Chemostratigraphic:

Two events are recognised in Blue Lias Formation beds 13-15, a 0.61 m-thick shale unit, the base of which is the boundary level advocated in this GSSP proposal; these should be capable of recognition across all facies as close proxies for the appearance of *Psiloceras planorbis*.

a) A prominent $\delta^{13}C_{org}$ negative excursion to –29.95 and a corresponding major peak in TOC in the 'Main Isotope Excursion' of Hesselbo *et al.* (2002) (Fig. 4). Hesselbo *et al.* (2002, fig. 4) demonstrated the stability of the $\delta^{13}C_{org}$ chemostratigraphy and its utility for correlation, using sections in East Greenland, Hungary and British Columbia, Canada. Additional comparative data is now available from Hungary (Pálfy *et al.*, 2007) and British Columbia (Ward *et al.*, 2004; Williford *et al.*, 2007), and there are also records from sections in Austria (McRoberts *et al.*, 1997; Kuerschner *et al.*, 2007), Italy (Galli *et al.*, 2005, 2007), Nevada, USA (Guex *et al.*, 2003, 2004; Lucas *et al.*, 2007; Ward *et al.*, 2007), Slovakia (Michalik *et al.*, 2007), Spain (Gómez *et al.*, 2007) and Tibet (Yin *et al.*, 2006).

b) The major peaks in Re and Os abundance documented from Blue Lias Formation bed 14 (Cohen & Coe, 2002).

Biostratigraphic:

a) Ammonite: the FAD of *Neophyllites* <0.5 m below the candidate GSSP level, in Blue Lias Formation bed 9 (see ***6.1.1***).

b) Foraminifer: the LAD of *Lingulina tenera* var. *octocosta*, approximating to the candidate GSSP level (Fig. 8).

13.2.2. One metre or more below the candidate GSSP level

Chemostratigraphic:

The maximum positive point between the 'Initial' and 'Main' negative carbon isotope excursions of Hesselbo *et al.* (2002), in Blue Lias Formation bed 1, c.4.25 m below the candidate GSSP level (Fig. 4). The maximum negative point in the 'Initial Isotope Excursion' of Hesselbo *et al.* (2002), around the Cotham Member – Langport Member boundary in the Lilstock Formation, c.6.85 m below the candidate GSSP level (Fig. 4).

Biostratigraphic:

a) Calcareous nannoplankton: the FAD of *Schizosphaerella punctulata* c.1 m below the candidate GSSP level in Blue Lias Formation bed 7, above the incoming of calcareous nannoplankton, represented by *Crucirhabdus primulus* (see ***6.3.3***) in the basal part of a TST (see **10**).

b) Miospores: the LADs of *Rhaetipollis germanicus* and *Ricciisporites tuberculatus* in Blue Lias Formation bed 5, c.3.2 m below the candidate GSSP level.

c) Conodonts: the LAD of these fossils in the upper part of the Langport Member in nearby sections (see ***6.2.3***; Fig. 14), c.5.8 m below the candidate GSSP level.

d) Foraminifers: the *Eoguttulina liassica* – JF1 foraminifer zone boundary in the upper part of the Langport Member, c.6 m below the candidate GSSP level.

Magnetostratigraphic:

The SA5r/SA6n polarity boundary (Hounslow *et al*., 2004, fig. 3) in Blue Lias Formation bed 1 (Fig. 3), c.4.5 m below the candidate GSSP level. A correlation of the magnetostratigraphic profiles from St Audrie's Bay and the Newark Basin continental succession (NE U.S.A) was proposed by Hounslow *et al.* (2004). An alternative correlation was proposed by Whiteside *et al.* (2007, figs 2, 7 (NB: the Blue Lias Formation is misnamed 'Blue Anchor Formation' in these figures)), and discussed by Lucas and Tanner (2007).

13.2.3. More than 1 m above the candidate GSSP level

Chemostratigraphic:

Prominent $\delta^{13}C_{org}$ negative excursions to –30.03 and –30.23 in the Planorbis Subzone (Blue Lias Formation beds 17 and 24), c.1.25 and 2.45 m above the candidate GSSP level respectively (Fig. 4)

Biostratigraphic:

a) Palynomorphs: the LAD of *Rhaetogonyaulax rhaetica*, marking the top of the Rrh dinoflagellate cyst interval biozone in Blue Lias Formation bed 24, c.3.6 m above the candidate GSSP level (Figs 10, 12).

b) Foraminifers: the LAD of *Vaginulina anomala* and the FAD of *V. curva* in the Planorbis Subzone <c.4.6m above the candidate GSSP level, below Blue Lias Formation beds 25 to 30 (Fig. 8).

The JF1 – JF2 foraminifer zone boundary in the upper part of the Johnstoni Subzone <c.7.8 m above the candidate GSSP level, below Blue Lias Formation bed 43 (Fig. 8).

c) Ammonites: the FADs of *Caloceras*, marking the base of the Johnstoni Subzone between 3.76 and 4.65 m above the candidate GSSP level, in Blue Lias Formation bed 25 (Page, 2005), 29 (Ivimey-Cook & Donovan, 1983) or 30 (Whittaker & Green, 1983, see **18**), and of *Waehneroceras* in bed 43, marking the boundary of the Planorbis and Liasicus zones c.7.8 m above the candidate GSSP level.

14. DEFINITION

The candidate GSSP horizon is defined as the base of Blue Lias Formation bed 13 of Whittaker and Green (1983). This is the lowest level from which definite *Psiloceras planorbis* have been recorded within the succession of psiloceratid ammonites documented from that formation in the St Audrie's Bay – Doniford Bay section (Bloos & Page, 1997a, b, 2000; Page & Bloos, 1998; Page, 2005) (see ***6.1.1***). This definition is supported by a wide range of bio- and non-biostratigraphic proxies (see **13.2**). The candidate GSSP site is the headland [ST 1020 4330] between St Audrie's Bay and Doniford Bay on the west Somerset coast, south-west England (Figs 1B, 2a,b,d,e,h). The candidate GSSP level, and the proposed base of the Planorbis Subchronozone, defining the base of the lowest classical Hettangian Standard (ammonite) Zone, correspond with the base of the *planorbis* biohorizon.

15. SUMMARY OF QUALIFYING ATTRIBUTES FOR CANDIDATE GSSP STATUS

In relation to ICS guidelines and requirements for GSSP selection (Remane, 1996; Remane *et al.*, 1996; summarised *in* Murphy & Salvador, 1999: 269), the candidate GSSP has the following attributes that fulfil these requirements comprehensively:

15.1. Geological requirements

15.1.1. Good exposure of an adequate thickness of sediments: c.200 m exposed and accessible in a largely near-dip section in near-vertical coastal cliffs and bedding surfaces on the contiguous foreshore; comprises constituent formations of the upper Mercia Mudstone, Penarth and lower Lias groups, and covers the Late Triassic (Norian) to Early Jurassic (Hettangian, Angulata Zone) interval. The Hettangian/Sinemurian boundary occurs in contiguous foreshore outcrops and the Sinemurian GSSP, defining the top of the Hettangian Stage, is already established nearby (see **3** – **5**).

15.1.2. Continuous sedimentation: no major stratigraphic gaps occur in the succession in the St Audrie's Bay to Doniford Bay section. A sequence boundary occurs within the Cotham Member (Lilstock Formation), c.7.5 m below the candidate GSSP horizon (see ***5.2.2***, **10**). Gamma ray correlation of the St Audrie's Bay succession with that at St Mary's Well Bay, [ST 176 677 to ST 187 681], Glamorgan, South wales, suggests that the upper part of the Johnstoni Subzone in that section may be absent at St Audrie's Bay (see **12**). The ammonite succession below the candidate GSSP horizon may be condensed relative to sections elsewhere in the UK but that above the horizon is not (see **13.1**).

15.1.3. Adequate rate of sedimentation: the candidate GSSP horizon is within a lithostratigraphic unit (the Blue Lias Formation) in which the rate of sedimentation is considered to have been sufficient for successive events (e.g. ammonite biohorizons, see ***6.1.1***) to be easily separated. (see discussion in **11** above.)

15.1.4. Absence of synsedimentary and tectonic disturbances: synsedimentary disturbance occurs within the Cotham Member (Lilstock Formation), c.7.5 m below the candidate GSSP horizon (see ***5.2.2***). The succession containing the candidate GSSP dips consistently southwestwards; small-scale faulting occurs but does not impede stratigraphic interpretation or identification of the candidate GSSP level (see **4**).

15.1.5. Absence of metamorphism and strong diagnetic alteration: no post-Hettangian igneous bodies occur in the region of the candidate GSSP; only very low-level heating is indicated by a CAI of <1 (see ***6.2.3***). No strong diagenetic effects have been reported. Diagenesis has not obscured or destroyed ichno- and other fabrics or fossils; ^{87}Sr/^{86}Sr ratios have been affected (see ***8.1.2***) but there is no indication, from clay mineralogy (see **9**), of significant burial or thermal diagenesis.

15.2. Biostratigraphic requirements

15.2.1. Abundance and diversity of well-preserved fossils: abundant and diverse microfloral and micro- and macrofaunal remains occur in the upper part of the Mercia Mudstone Group (Blue Anchor Formation), the Penarth Group, and the Lias Group (see **6**). The appearance of *Psiloceras planorbis* in relative abundance characterises the candidate GSSP level, below which ammonites, comprising other psiloceratids, are scarce (see ***6.1.1***, ***15.3.6***).

15.2.2. Proximity to vertical facies changes: the candidate GSSP horizon is c.5.6 m above a vertical facies change from a shallow marine carbonate facies (Langport Member;

Lilstock Formation) to alternating marine mudstone and limestone (Blue Lias Formation).

15.2.3. Facies favourable for long-range biostratigraphic correlation**:** the candidate GSSP horizon is within an established open marine sequence, c.5.6 m above the base of the fossiliferous Blue Lias Formation.

15.3. Other methods and requirements

15.3.1. Magnetostratigraphy**:** documented from the Mercia Mudstone Group to Lias Group (early Hettangian) succession (see **7**).

15.3.2. Chemostratigraphy**:** $\delta^{13}C_{org}$ data are available from the Williton Member (Blue Anchor Formation) to Blue Lias Formation (Hettangian, Liasicus Zone) succession and Re and Os data from the Westbury Formation (Penarth Group) and Lias Group (Hettangian, Planorbis Zone) (see **8**).

15.3.3. Sequence stratigraphy**:** the candidate GSSP is within a Transgressive Systems Tract initiated during deposition of the underlying Penarth Group (see **10**).

15.3.4. Historical priority, usage, and approximation to traditional boundaries**:** the candidate GSSP level corresponds with the classical base of the Hettangian Stage, at the base of the Psiloceras Subchronozone, and is marked by the appearance of the index fossil *Psiloceras planorbis* within a widely recognised succession of ammonite faunas (see **2** and ***6.1.1***).

15.3.5. Outcrop condition: the candidate GSSP site is a coastal cliff and is free from a permanent cover or accumulations of weathered debris (Figs 2a,b,d,e).

15.3.6. Identification of the candidate GSSP level**:** interpretation of the section presents no problems and the candidate GSSP level (Figs 2b,d,e) is readily identifiable at the incoming of abundant specimens of *Psiloceras planorbis* in Blue Lias Formation bed 13; other psiloceratids occur in lower beds but, in contrast, are scarce.

15.3.7. Accessibility**:** the candidate GSSP site is easily reached by private or public transport; it is at beach level and is readily accessible except around times of high tide.

15.3.8. Freedom of access**:** there is no restriction on access to the coast section that includes the candidate GSSP; Natural England, Taunton, must be contacted regarding sampling and collecting.

15.3.9. Protection**:** the candidate GSSP is within a Site of Special Scientific Interest (SSSI) protected under UK law and is listed in the Geological Conservation Review as a site of national and international importance. The Sinemurian GSSP, defining the top of the Hettangian Stage, has been established nearby in the same SSSI.

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18. APPENDIX

Log of the St Audrie's Bay to Doniford Bay cliff section [ST 1200 4375 to 0979 4332] containing the candidate Hettangian GSSP level (red line) (from Whittaker & Green, 1983: 54-55, 66, 68; * part of 'Watchet Beds' bed 1 of Richardson (1911) included in the Langport Member by Whittaker (1978; see Whittaker & Green, 1983, fig. 12, and 5.2.2)).

Bed No.	Lithology and fauna	Thickness (m)	
LIAS GROUP			
BLUE LIAS FORMATION			
	Angulata Zone		
130-135	Shales with two limestone bands at middle and base		1.12
129	Shales with nodular and lenticular limestones near the base	1.85	
128	Limestone, lenticular in places		0.10-01.5
127	Shale		0.76
126	Limestone. *Calcirhynchia* sp.		0.30-0.33
124-125	Shale. Large *Schlotheimia*		2.04
117-123	Limestones in three bands alternating with shales	1.14	
115-116	Shale		2.87
107-114	Limestones in four bands alternating with shales	1.26	
106	Shale		1.50
103-105	Limestones in two bands with shale between		0.43
102	Shale		1.22
101	Limestones with a shale parting		0.46
100	Shale		0.41
99	Limestones in three bands separated by shales		0.69
98	Shale		0.41
97	Limestone		0.33
96	Shales with three limestone bands		2.43
94-95	Limestones in two bands alternating with shale	1.93	
93	Limestone, lenticular		0.05-0.10
92	Shale		0.91
91	Limestone, lenticular		0.05-0.10
	Shale		0.13
	Limestone, slabby and regular		0.09
90	Shale		1.40
89	Limestones in five bands alternating with shales	1.59	
88	Shale		1.63
87	Limestone in three bands separated by shales		0.84
80-86	Shales with two bands of limestone		4.78
	Liasicus Zone		
79	Limestones in nine bands alternating with shale	2.46	
78	Shales with three limestone bands		2.10
77	Limestone, lenticular		0-0.10
76	Shale		1.09
75	Limestone, in places present as two beds		0.20-0.28
74	Shale		1.09
73	Limestones with a mudstone parting		0.38
72	Mudstone		0.43
71	Limestone, lenticular		0.05-0.10
70	Shale		0.20-0.25
69	Limestone, persistent but slightly lenticular in places		0.23-0.25
66-68	Shales, mainly fissile but some calcareous and blocky. *Laqueoceras laqueus*,		

	Waehneroceras cf. *megastoma* and *W. portlocki*	4.37	
65	Limestone, persistent		0.08-0.10
62-64	Shale, blocky in lowest 0.30m. *W.* cf. *megastoma* and *W. portlocki*		2.28
57-61	Shale, with flat limestone lenses and nodules in topmost 0.05m. *Heterastrea* sp., *Waehneroceras megastoma*, *W. portlocki* and *Psilophyllites* sp.		2.21
56	Mudstone		0.51
55	Limestone, persistent nodule bed		0-0.15
50-54	Shale and calcareous mudstone. *Psilophyllites*? and *Waehneroceras* sp.		4.53
49	Shale and mudstone, very calcareous		0.46
	Limestone, elongated large nodules		0-0.20
46-48	Shale and mudstone. *Lucina limbata*		0.71
45	Shale. *Psilophyllites* sp. and *Waehneroceras* sp.	2.23	
	Limestone nodules	0-0.10	
43-44	Shale and mudstone. *Camptonectes* sp. and *Plagiostoma* sp.; *Waehneroceras prometheus* at base	2.67	

Planorbis Zone

38-42	Limestone in two bands with mudstone parting	0.41	
	Shale, blocky in topmost 0.48m. *Caloceras johnstoni* and *C. intermedium*		1.42
35	Limestones in two bands with a shale parting		0.22
32-34	Shales with a limestone band	0.29	
31	Limestone, 'beefy'		0.10
	Shale		0.15-0.18
	Limestone		0.19
30	Shale. *Caloceras* sp.		0.38-0.46
25-29	Limestones in three bands alternating with mudstones		0.89
23-24	Shale. Abundant *Psiloceras planorbis*, *P. plicatulum*, *Anningella faberi*, echinoid and fish fragments		1.93
20-22	Limestone		0.28
17-19	Shale. *P. planorbis*	0.64	
16	Limestone		0.30
13-15	Shale. *P. planorbis*, *Liostrea irregularis*, echinoid fragments and thin-shelled bivalves cf. *Anningella*		0.61

Pre-planorbis Beds

12	Limestone in one or two nodular beds	0.13-0.20	
9-11	Shale		0.20-0.23
8	Limestone, slightly lenticular	0.22	
7	Shales with a limestone band near base	0.78	
	Limestone passing laterally into hard calcareous mudstone	0.06	
	Shale. *Protocardia* sp. and echinoid fragments		0.24
	Limestone or hard calcareous mudstone	0.08	
	Shale		0.05
	Limestone		0.08
	Shale. *Pteromya tatei*		0.44
6	Limestone, persistent but lenticular		0.10-0.17
	Shale, with nodular limestone up to 0.13m thick and with bivalves	0.17	
	Limestone, massive, somewhat 'beefy'	0.30-0.33	
5.	Shale, with persistent shelly bands and silty laminae. *Plagiostoma* sp. and *Pteromya tatei*		0.43
4	Limestone, impersistent		0-0.08
	Shale parting, not always present		0-0.03
	Limestone, with shelly bands; somewhat 'beefy' and laminated in places		0.38-0.46
3	Shale		0.23
2	Limestone, laminated		0.11
1	Shale with silty laminations	1.42	

PENARTH GROUP

LILSTOCK FORMATION

Langport Member

*	Mudstone, grey, with a green tint and with impersistent limestones	0.74	
1-3	Limestones, brownish grey, fine-grained, hard and splintery and divisible into four beds. The top is somewhat irregular. The lowest bed is composed of rubbly limestone and has an irregular base		0.30-0.33
4	Mudstone, greenish grey, marly, silty and blocky. More fissile in the lowest 0.10m		0.30-0.33
5	Limestone, pale grey, silty, with calcite stringers; fairly regular and uniform laterally		0.09-0.10
6	Mudstone, grey, marly, rather blocky		0.05-0.06

	Limestone, grey, hard, splintery, with scattered pyrite. Locally in two (0.05m-thick) beds separated by a mudstone parting	0.10	
7-11	Mudstone, dark grey, marly and rather shaly		0.06
	Limestone, grey, hard, very fine-grained, almost porcellanous; laminated and with vertical calcite stringers		0.10-0.15
	Marl, grey		0.03
	Limestone, pale grey, fine-grained, porcellanous, splintery, with a conchoidal fracture. Not everywhere present		0-0.05

Cotham Member

2	Shale, greenish grey, laminated, fairly blocky in the top 0.08m		0.38-0.46
3	Sandstone, greenish grey. Small cavities are present in a band 0.05m below the top; the bed is laminated in the lowest 0.06m	0.15-0.18	
	Marl, greenish grey or green, fairly fissile		0.03
	Sandstone, dark greenish grey		0.03-0.04
	Siltstone, greenish grey, hard, marly. Contortions and slump structures are present in the top half; the bed is laminated below	0.20-0.28	
4	Mudstone, green or olive-green; marly but fairly fissile in the top 0.15m and the bottom 0.10m		0.43
	Siltstone or silty marl, hard calcareous; somewhat laminated, with lensoid partings		0.15-0.19
	Marl, pale green, rather fissile, with contorted harder beds in places	0.63	

WESTBURY FORMATION

5a	Shale, black		0.05m
	Shale, black: a lensoid band with intercalated green marl		0.03-0.05
	Shale, black, with green marl wisps and partings	0.05-0.08	
	'Beef'		0.03-0.05
	Shale, black		0.53-0.61
	'Beef'		0.03-0.05
	Limestone, very dark grey, earthy		0.03-0.05
	'Beef'		0.03-0.08
	Shale, black		0.91-0.97
5b-7	'Beef'		0.05-0.08
	Limestone, dark grey, earthy	0.08-0.10	
	Shale, black		0.03
	Limestone, dark grey, earthy	0.13-0.20	
	'Beef'		0.03
	Shale, black	(seen)	0.15

FIGURE CAPTIONS

Figures 1A, B. Locality maps.

Figures 2a – j. The candidate Hettangian GSSP site and contiguous sections (photographs by G. Warrington).

2a. St Audrie's Bay; view westwards to the headland separating this bay from Doniford Bay. The arrow indicates the candidate GSSP site.

2b. St Audrie's Bay; view southeastwards from the candidate GSSP site (right foreground; arrow marks the candidate GSSP level), in the Blue Lias Formation outcrop, to a cliff (background) in which, from left (access point to beach level) to right, the topmost Branscombe Mudstone Formation and succeeding Blue Anchor Formation (Mercia Mudstone Group), overlain by the Penarth Group (vegetated area at the cliff top, centre) are exposed.

2c. St Audrie's Bay; view eastwards from the candidate GSSP site (see 2b) to cliffs in which, from right to left, the Blue Anchor Formation (grey-green) and the underlying, mainly red-brown, Branscombe Mudstone Formation of the Mercia Mudstone Group are exposed.

2d-e. The candidate GSSP site with the candidate GSSP level marked by the arrow; the cliff in 2d shows Blue Lias Formation beds 4 to 29 (see Fig. 3); bed numbers around the candidate GSSP level are indicated in 2e. Scale: hammer 0.35 m (above arrow).

2f. *Psiloceras planorbis* (J. de C. Sowerby). Lectotype: specimen BM 43875, Natural History Museum, London.

2g. *Psiloceras planorbis* on a bedding surface exposed on the foreshore adjacent to the candidate GSSP site.

2h – i. Exposures of the Blue Lias Formation westwards from the candidate GSSP site (2h, extreme left; arrow marks the candidate GSSP level) into Doniford Bay. The highest beds seen in 2i are in the Angulata Zone.

2j. View eastwards from the west side of Doniford Bay showing extensive exposures visible on the foreshore at low tide, the candidate Hettangian GSSP site (H: 2.5 km), the Sinemurian GSSP site (S: 6 km) and, at the far left, a headland (9 km) near Lilstock and the eastern end of the Blue Anchor to Lilstock SSSI. The Quantock Hills (Devonian) form the skyline in the right half of the view.

Figure 3. Magnetostratigraphy of the Penarth Group and lower Lias Group succession at St Audrie's Bay, in relation to the lithostratigraphy and main bio- and chemostratigraphic features (after Hounslow *et al*., 2004, fig. 3, by courtesy of Dr M. W. Hounslow). Red line – candidate GSSP level.

Figure 4. Carbon isotope stratigraphy of the upper Blue Anchor Formation to lower Blue Lias Formation succession at St Audrie's Bay, in relation to %CARB, %TOC, sequence stratigraphy and sea level change, lithostratigraphy, magnetostratigraphy, and the main biostratigraphic features (after Hesselbo *et al*., 2004a, fig. 4, by courtesy of Dr S. P. Hesselbo). Red line – candidate GSSP level. Green line – start of Main carbon-isotope excursion. The position of the dinoflagellate cyst zone boundary shown by Hesselbo *et al.* is based on Woollam and Riding (1983) and has been modified (see 6.3.2). The boundary proposed by Warrington *et al.* (1994) was the base of bed 13 of Whittaker and Green (1983) not, as shown by Hesselbo *et al*., the base of bed 8, which was the level proposed by Warrington and Ivimey-Cook, 1995 (see ***6.1.1***).

Figure 5. Ammonite succession in the Blue Lias Formation at St Audrie's Bay and Doniford Bay (after Page, 2005).

Figure 6. Bivalves from the Blue Anchor Formation to Blue Lias Formation succession at St Audrie's Bay and Doniford Bay.

Figure 7. Macrofauna, other than bivalves and ammonites, from the Blue Anchor Formation to Blue Lias Formation succession at St Audrie's Bay and Doniford Bay.

Figure 8. Foraminifera from the Blue Anchor Formation to Blue Lias Formation succession at St Audrie's Bay, Doniford Bay, and other west Somerset coast and eastern Bristol Channel localities.

Figure 9. Ostracods from the Penarth Group and Blue Lias Formation at St Audrie's Bay, Doniford Bay, and other west Somerset coastal localities.

Figure 10. Distribution and relative abundances of palynomorphs in the upper Branscombe Mudstone Formation to lower Blue Lias Formation succession at St Audrie's Bay (after Warrington, *in* Hounslow *et al*., 2004, fig. 5). Red line – candidate GSSP level.

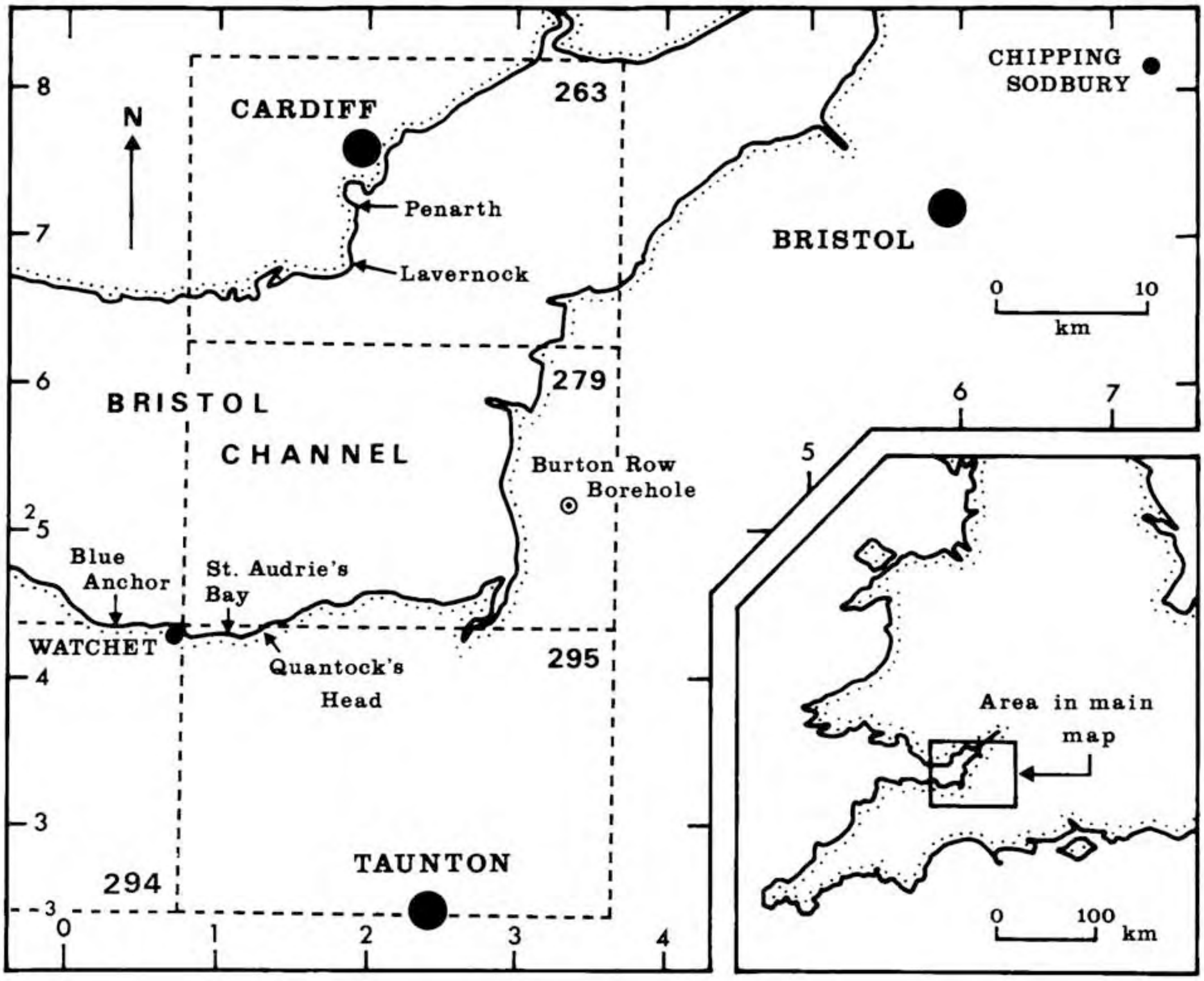
Figure 11. Numbers of genera and species in spore, non-spore and total miospore associations from the upper Branscombe Mudstone Formation to lower Blue Lias Formation succession at St Audrie's Bay (Warrington, ms. records).

Figure 12. First and last occurrences of selected palynomorphs in the Blue Anchor Formation to Blue Lias Formation succession at St Audrie's Bay.

Figure 13. Biostratigraphic schemes applicable to the Blue Anchor Formation to Charmouth Mudstone Formation succession at St Audrie's Bay and Doniford Bay.

Figure 14. Proxies for the candidate GSSP in the St Audrie's Bay – Doniford Bay section.

A



B

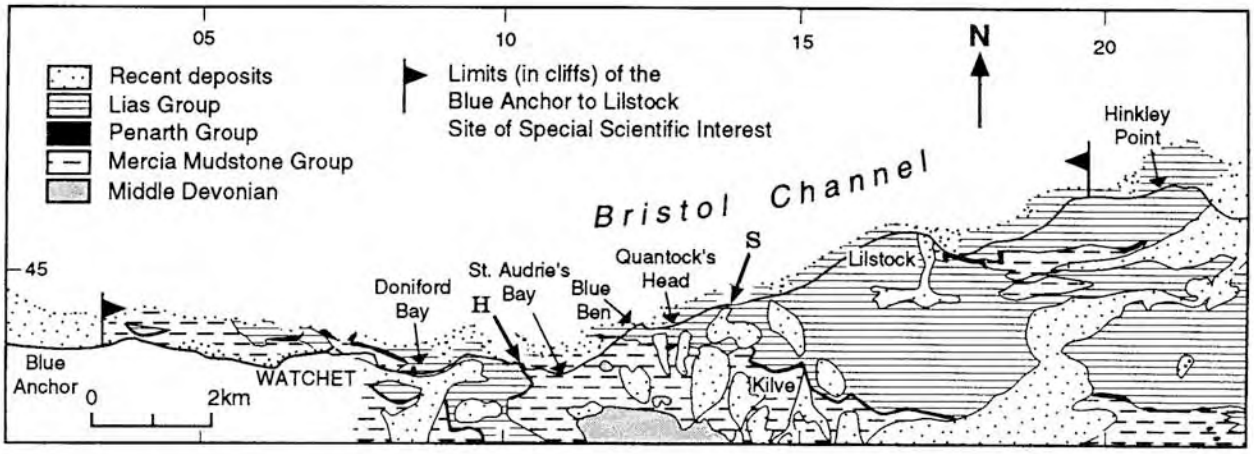
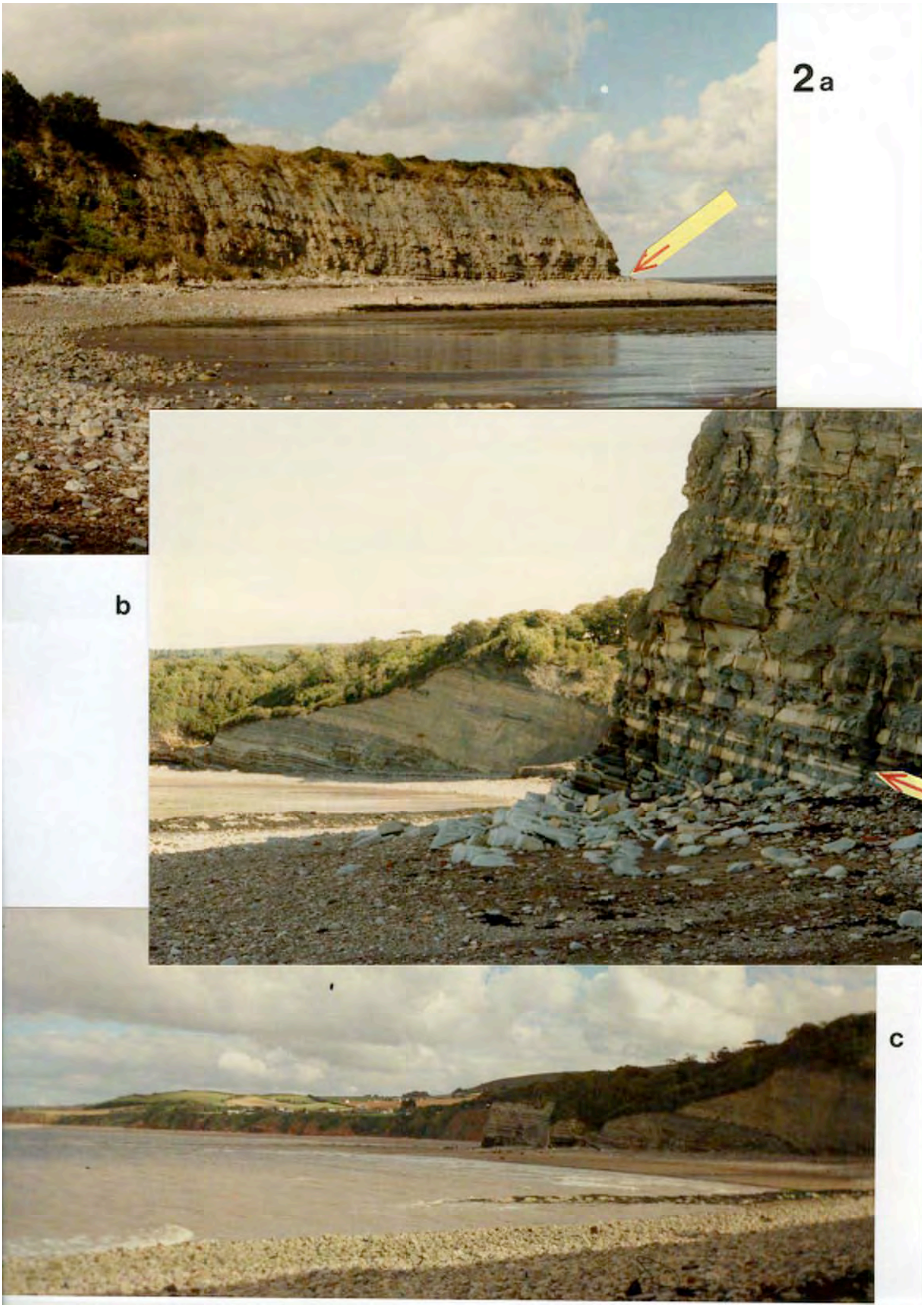


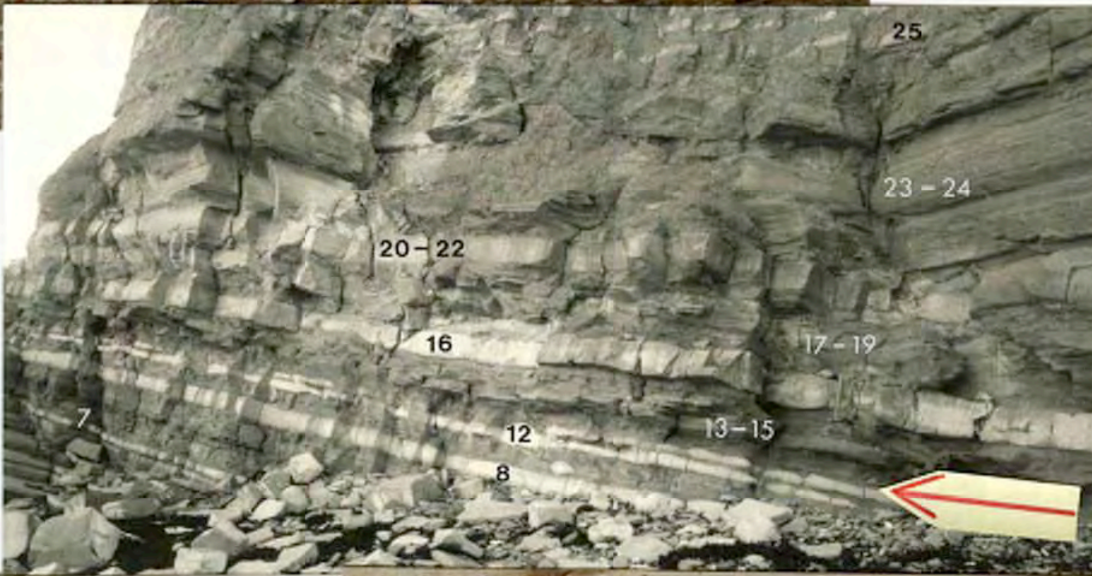
Figure 1. Locality maps

A – Bristol Channel region with sites mentioned in the text and boundaries of British Geological Survey maps 263 (Cardiff), 279 (Weston-super-Mare), 294 (Minehead, *pars.*) and 295 (Taunton) (after Warrington *et al.*, 1994, fig.1).
B – the west Somerset coast (H - candidate Hettangian GSSP site, S – site of Sinemurian GSSP) (after Warrington & Ivimey-Cook, 1995, fig. 3).


2a
b
c

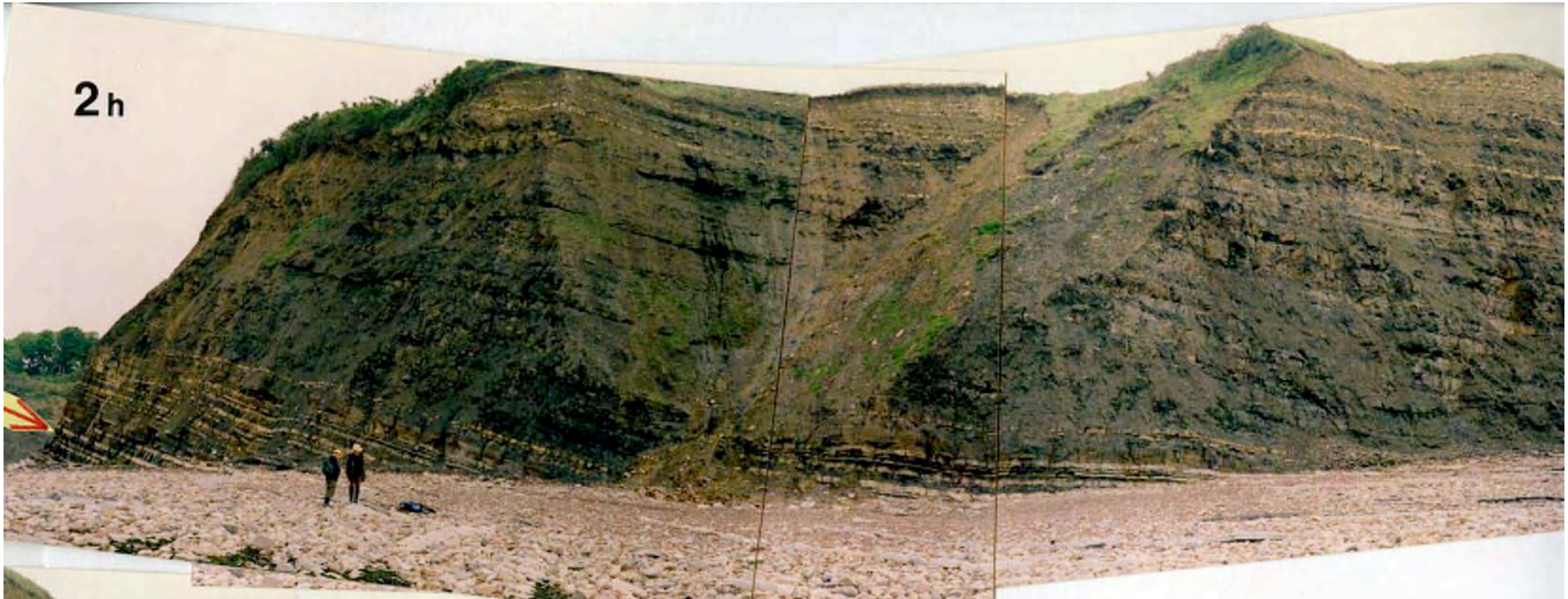
2d

e



f

g



2h

2i

2j

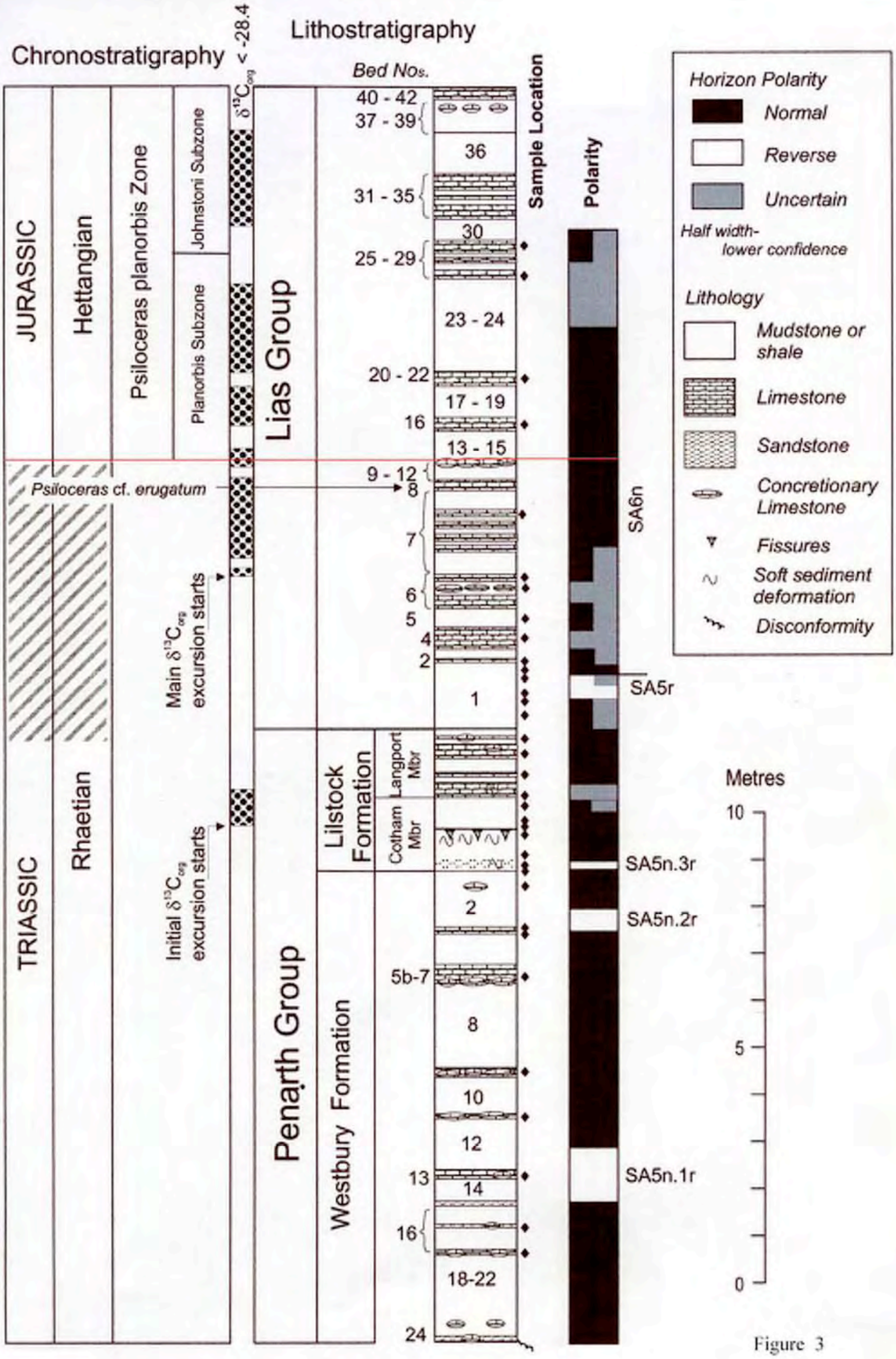

Chronostratigraphy
$\delta^{13}C_{org}$ < -28.4
Lithostratigraphy
Bed Nos.
Sample Location
Polarity
JURASSIC
Hettangian
Psiloceras planorbis Zone
Johnstoni Subzone
Planorbis Subzone
Psiloceras cf. erugatum
TRIASSIC
Rhaetian
Main $\delta^{13}C_{org}$ excursion starts
Initial $\delta^{13}C_{org}$ excursion starts
Lias Group
Penarth Group
Lilstock Formation
Langport Mbr
Cotham Mbr
Westbury Formation
40 - 42
37 - 39
36
31 - 35
30
25 - 29
23 - 24
20 - 22
17 - 19
16
13 - 15
9 - 12
8
7
6
5
4
2
1
2
5b-7
8
10
12
13
14
16
18-22
24
SA6n
SA5r
SA5n.3r
SA5n.2r
SA5n.1r
Horizon Polarity
Normal
Reverse
Uncertain
Half width- lower confidence
Lithology
Mudstone or shale
Limestone
Sandstone
Concretionary Limestone
Fissures
Soft sediment deformation
Disconformity
Metres
10
5
0

Figure 3

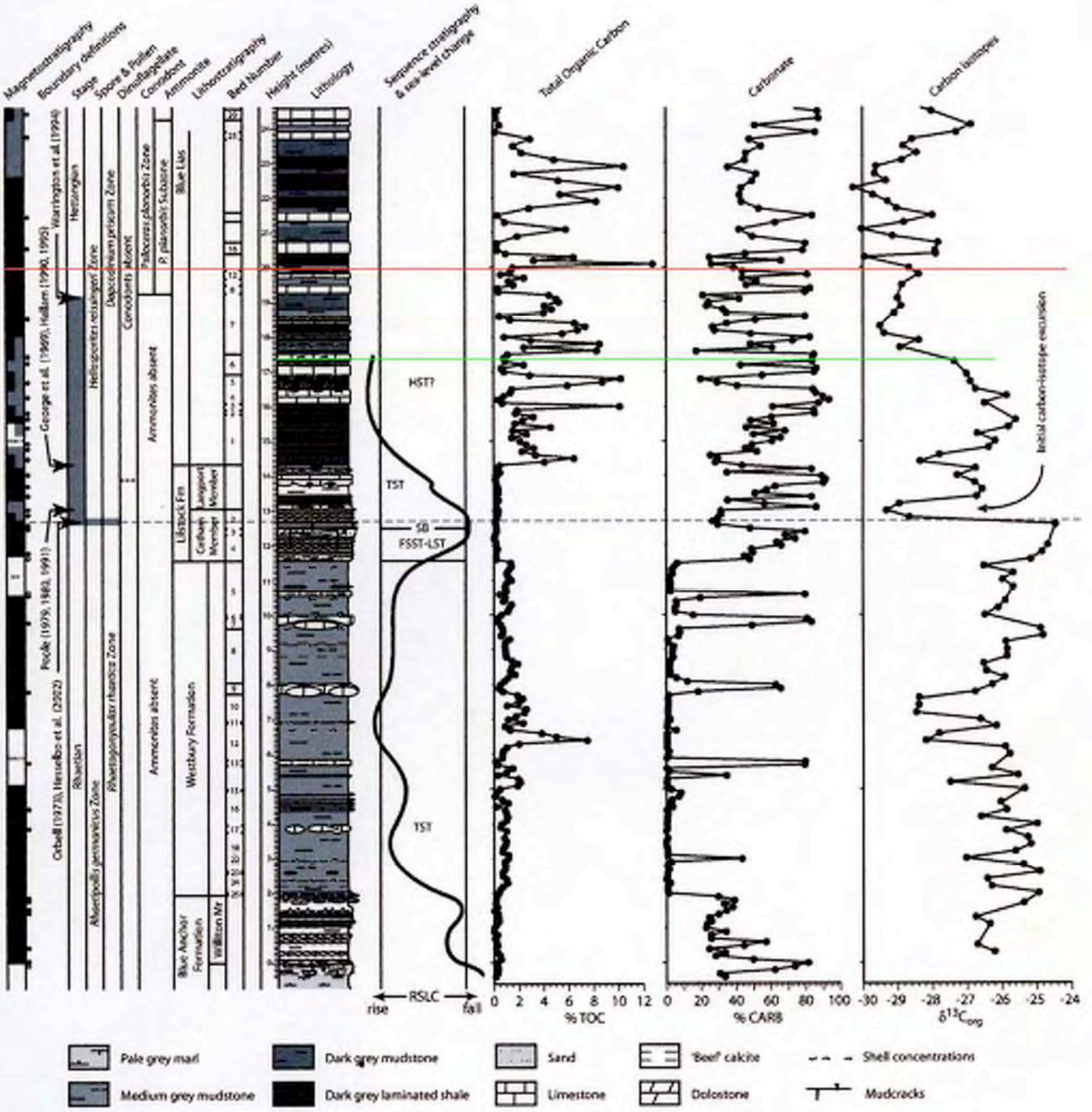

Magnetostratigraphy
Boundary definitions
Stage
Spore & Pollen
Dinoflagellate
Conodont
Ammonite
Lithostratigraphy
Bed Number
Height (metres)
Lithology
Sequence stratigraphy & sea-level change
Total Organic Carbon
Carbonate
Carbon isotopes
Orbell (1973), Hesselbo et al. (2002)
Poole (1979, 1980, 1991)
George et al. (1969), Hallam (1990, 1995)
Warrington et al. (1994)
Rhaetian
Hettangian
Rhaetipollis germanicus Zone
Heliosporites reissingeri Zone
Rhaetogonyaulax rhaetica Zone
Dapcodinium priscum Zone
Conodonts absent
Ammonites absent
Psiloceras planorbis Zone
P. planorbis Subzone
Blue Lias
Lilstock Fm
Langport Member
Cotham Member
Westbury Formation
Blue Anchor Formation
Williton Mr
HST?
TST
SB
FSST-LST
TST
Initial carbon-isotope excursion
rise
RSLC
fall
0 2 4 6 8 10 12
% TOC
0 20 40 60 80 100
% CARB
-30 -29 -28 -27 -26 -25 -24
δ13Corg
Pale grey marl
Medium grey mudstone
Dark grey mudstone
Dark grey laminated shale
Sand
Limestone
'Beef' calcite
Dolostone
Shell concentrations
Mudcracks

Figure 4

STAGE	Zone	Subzone	Ammonite taxa	Bed and level of appearance or presence	Range up to bed	Biohorizon
Sinemurian	Bucklandi	Conybeari	*Vermiceras palmeri*, *V. quantoxense*	146 (0.6-0.53m below the top)		
Hettangian	Angulata	Depressa	*Schlotheimia* ex grp *pseudomoreana*	135 (0.04-0.05m above the base)	146 (c.0.7-0.87m below the top)	*pseudomoreana*
			Large schlotheimids, including *S.* ex grp *princeps*	134 (top surface)		*depressa* ?
		Complanata	*Schlotheimia* ex grp *striatissima*	133		*striatissima* ?
			Schlotheimia complanata	131 (0.35m above the base)		
			Schlotheimia oxygonia	131 (c.0.3m below the top)		
			Schlotheimia polyeides, *S.* sp.cf. *macilenta*	129 (c.0.15m above the base)		
			Schlotheimia sp. cf. *transiens*	125		
			Schlotheimia cf. *tenuis*	115-116 (c.0.6-0.7m below the top)		
			Schlotheimia phoebetica	111 and/or 110?		
			Schlotheimia cf. *angulosa*	102 (c.0.6m above the base)	129 (c.1.3m below the top)	
			Schlotheimia sp. cf. *complanata*	102 (c.0.6m above the base)	127	
			Schlotheimia cf. *oxygonia*	102		
			(unspecified species compatible with the subchronozone	93-96		*similis*
		Extranodosa	*Schlotheimia*	89		
			Schlotheimia cf. *amblygonia*	80	82	*amblygonia*
	Liasicus	Laqueus	*Alsatites* sp., *Waehneroceras* sp. cf. grp *schroederi*, ?*Psilophyllites* sp.	74		*laqueolus* ?
			Alsatites	68, 69		
			Alsatites (*Laqueoceras*) *laqueus* (with *Waehneroceras*, including *W.* cf. *costatum*	67	68 (to at least 1.05m below the top)	*laqueus*
		Portlocki	*Waehneroceras* ex grp *schroederi*	57-61 (from 2.1m above the base)	At least 64	*schroederi*
			Waehneroceras ex grp *portlocki*	57-61 (1.5m above the base)		*stricklandi* - *portlocki*
			Psilophyllites hagenowi	57-61 (c.0.6-1.2m above the base)		*hagenowi*
			Curviceras sp., ?*Waehneroceras* (*Kammarkarites*) sp., ?*Psilophyllites* sp.	52		
			Waehneroceras (*Curviceras*) spp.[2]	43-44		*iapetus*
	Planorbis	Johnstoni	*Caloceras intermedium*	37	38?	*intermedium*
			Caloceras johnstoni	36 (c.0.2-0.6m above the base)		*johnstoni*
			Caloceras sp.	25	42	
		Planorbis	*Psiloceras* cf. *bristoviense*	23/24 (c.2.3-2.6m above the base)		
			Psiloceras ex grp *sampsoni*	23/24 (1.75-1.8m above the base)		*sampsoni* β
			Psiloceras plicatulum	23/24 (1.2-1.3m above the base)		*plicatulum*[1]
			Psiloceras (more evolute forms)	23/24 (0.6 to 1m above the base)		*sampsoni* α
			Psiloceras planorbis	13	Bed 23/24 (0.6m above the base)	*planorbis*
			Psiloceras s.s	9 (upper part)		
			Neophyllites ?	8 (top surface)		*imitans* and/or *antecedens*
			Psiloceras cf. *erugatum*	8		*erugatum*

Figure 5. Ammonite succession in the Blue Lias Formation at St Audrie's Bay and Doniford Bay (after Page, 2005)

[1] *plicatulum* Biohorizon restricted to the lower *Psiloceras* ex grp *plicatulum* fauna of Page and Bloos, 1998.

[2] the earliest *Waehneroceras* (*Curviceras*) include *W.* (*C.*) cf. *prometheus*

Red line – candidate Hettangian GSSP level (biohorizons below this level are currently included in the Planorbis Subzone (Page & Bloos, 1998; Page, 2005) (see **13.1**)

Blue line – top of Hettangian, defined by the Sinemurian GSSP (see **3**)

GROUP	Formation	Members and (ammonite) Zones	Bed number	*Mytilus* sp.	*Protocardia rhaetica*	*Gervillella praecursor*	*Isocyprina* sp.	*Rhaetavicula contorta*	*Chlamys valoniensis*	*Tutcheria cloacina*	*Modiolus* sp.	*Liostrea* sp.	*Lyriomyophoria postera*	*'Modiolus' sodburiensis*	*Placunopsis alpina*	*Isocyprina* (*E.*) *concentricum*	*'Permophorus'* sp.	*Pteromya* cf. *crowcombeia*	*Isocyprina* (*E.*) sp. nov.?	*'Permophorus' elongatus*	*Isocyprina* (*E.*) *ewaldi*	*Modiolus minimus*	*Ryderia titei*	*Cardinia* sp.	*Cardinia* cf. *regularis*	*Modiolus hillanus*	*Cercomya* sp.	*Atreta intusstriata*	*Isocyprina* (*E.*) *germari*	*Protocardia* sp.	*Pleuromya?* sp.	*Meleagrinella* sp.	*Plagiostoma giganteum*	*Liostrea hisingeri*	*Plagiostoma* sp.	*Ostrea* sp.	*Grammatodon lycetti*	*Myoconcha psilonoti*	*Pteromya tatei*	*Antiquilima succincta*	*Anningella* sp.	*Protocardia* cf. *philippianum*	*Anningella faberi*
LIAS	Blue Lias	liZ	43 to 44																																X								
		pZ	23 to 24																																								X
			22																																				X			X	
			16																															X									
			13 to 15																															X							cf.		
			7																			X								X			X	X					X	X			
			6																			X												X									
			5																			X												X	X				X				
			4																			X												X									
PENARTH	Lilstock	Langport	1'				?																														X	X					
			2'																															X									
			3'																															X									
			1								X	?																X						X	X	?							
			3																									X		X			X	X	X								
			4																							X				?	?	?											
			6								X																																
		Cotham	4		X	X			X	X					?	X									X			X		?													
	Westbury		5		X	X		X	X	X	X	?	X	X	X	X					X		X					X	X														
			6					X	X						X													X															
			7			X		X	X		X		X		X					X																							
			8		X			X		X	X				X	X				X							?																
			9					X					X		X																												
			10 to 12		X	X	X	X		X	X		X							X				X	?	X																	
			13						X				X							X	X		X																				
			14		X			X			X																																
			15																		?																						
			16				X	X					X																														
			17		X			?			?								X	X	X	X																					
			18 to 25														X	X																									
			26		X			X	X		X		?	X	X	X																											
			28 to 30		X	X	X	X	X	X	X	?																															
MM	BA	Williton				X																																					
		Rydon		?	X																																						

Figure 6. Bivalves from the Blue Anchor Formation to Blue Lias Formation succession at St Audrie's Bay and Doniford Bay

Sources: Richardson, 1911; Whittaker and Green, 1983; Hodges, 1994, and *in* Ivimey-Cook *et al*., 1999 (p.107), and *pers. comm*. to GW (August 2007); Ivimey-Cook (ms. records); Van de Schootbrugge *et al.,* 2007. Taxonomy after Ivimey-Cook *et al*., 1999. **X** - record; **?** - uncertain record

Abbreviations: BA – Blue Anchor Formation, liZ – Liasicus Zone, MM – Mercia Mudstone Group, pZ – Planorbis Zone. Bed numbers from Whittaker and Green (1983); 3^1, 2^1 and 1^1 are 'Watchet Beds' beds 3, 2 and 1 (*pars.*) of Richardson (1911), incorporated by Whittaker (1978) into the Lilstock Formation (Whittaker & Green, 1983) (see 5.2.2).

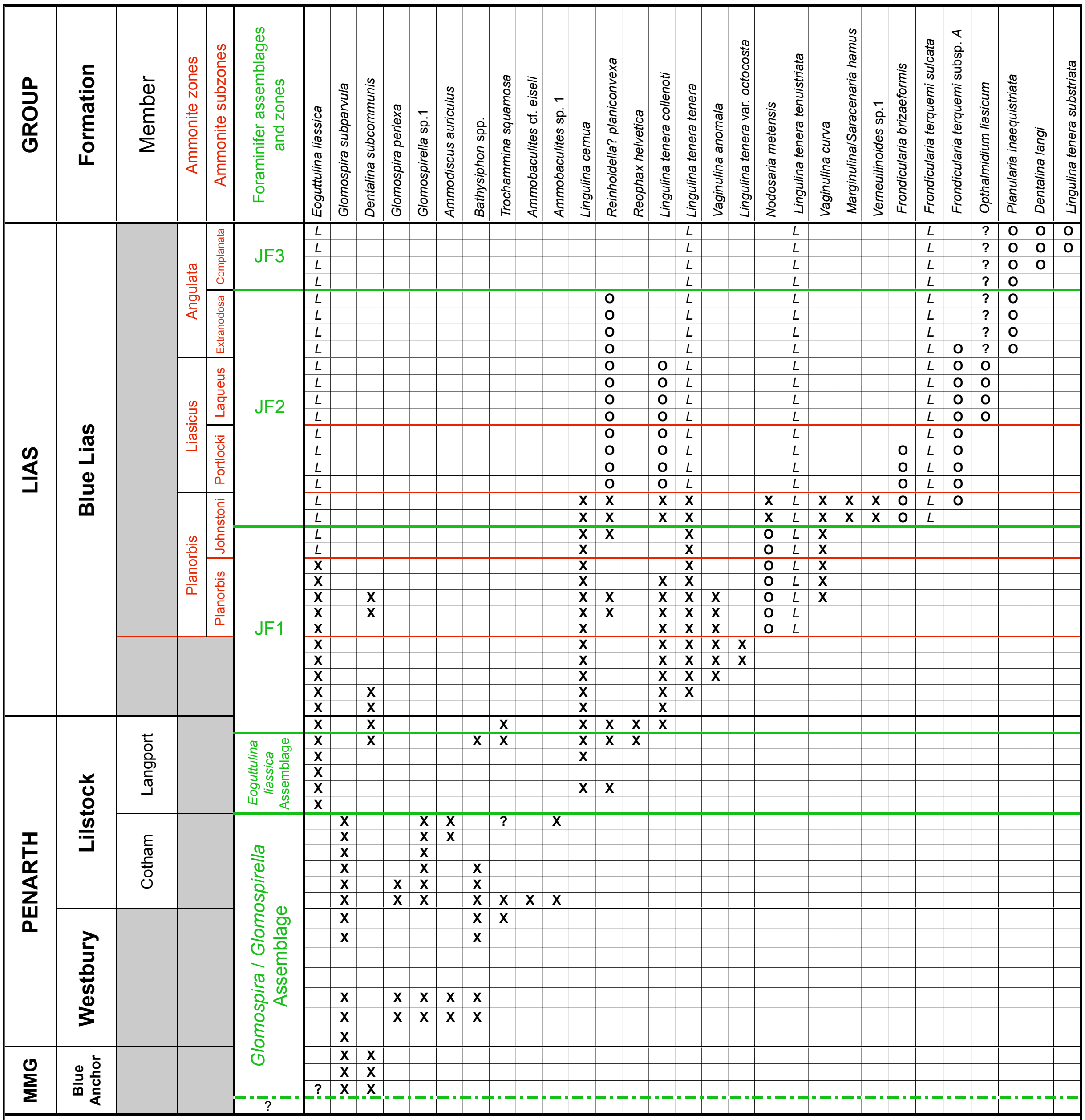
Red line – candidate Hettangian GSSP horizon.

GROUP	Formation	Members and (ammonite) Zone	Bed number	An	C	Gastropods					Echin		Fish								Misc.	
				Serpula	Coral (montlivaltiid?)	gastropod remains	*Naticopsina oppelii*	*Zygopleura henrici*	*Cylindrobullina fusiformis*	*Cylindrobullina ovalis*	*Aplocoma* sp.	echinoid remains	*'Hybodus'* cf. *cloacinus*	*'Sargodon'*	Fish teeth (*'Sphaerodus'*-type)	*Lissodus minimus*	*Gyrolepis albertii*	Fish remains/scales	*'Hybodus' minor*	*Agkistracanthus mitgelensis*	bone fragments	coprolites
L	**BL**	pZ	23 to 24									X						X				
			7									X										
PENARTH	**Li**	Langport	1 to 3		X							X										
		Cotham	2															X				
			4															X		X		
	Westbury		5	?			X		X	X	X											
			7															X				
			8															X				
			10 to 12				X											X				
			13					X														
			15													X	X				X	X
			16				X															
			17														X		X			
			26				X															
MM	**BA**	Williton														X	X	X				
		Rydon				X							X	X	X	X	X	X				

Figure 7. Macrofauna, other than bivalves and ammonites, from the Blue Anchor Formation to Blue Lias Formation succession at St Audrie's Bay and Doniford Bay

Sources: Richardson (1911), Whittaker and Green (1983), Duffin (1994, 1999). **X** - record **?** - uncertain record

Abbreviations: An – Annelids, BA – Blue Anchor Formation, BL – Blue Lias Formation, C – Corals, Echin – Echinoderms, L – Lias Group, Li – Lilstock Formation, Misc. – Miscellaneous remains, MM – Mercia Mudstone Group, pZ – Planorbis Zone.



GROUP	Formation	Member	Ammonite zones	Ammonite subzones	Foraminifer assemblages and zones	*Eoguttulina liassica*	*Glomospira subparvula*	*Dentalina subcommunis*	*Glomospira perlexa*	*Glomospirella sp.1*	*Ammodiscus auriculus*	*Bathysiphon spp.*	*Trochammina squamosa*	*Ammobaculites cf. eiseli*	*Ammobaculites sp. 1*	*Lingulina cernua*	*Reinholdella? planiconvexa*	*Reophax helvetica*	*Lingulina tenera collenoti*	*Lingulina tenera tenera*	*Vaginulina anomala*	*Lingulina tenera var. octocosta*	*Nodosaria metensis*	*Lingulina tenera tenuistriata*	*Vaginulina curva*	*Marginulina/Saracenaria hamus*	*Verneuilinoides sp.1*	*Frondicularia brizaeformis*	*Frondicularia terquemi sulcata*	*Frondicularia terquemi subsp. A*	*Opthalmidium liasicum*	*Planularia inaequistriata*	*Dentalina langi*	*Lingulina tenera substriata*
LIAS	Blue Lias		Angulata	Complanata	JF3	L														L				L					L		?	O	O	O
						L														L				L					L		?	O	O	O
						L														L				L					L		?	O	O	
						L														L				L					L		?	O		
				Extranodosa	JF2	L											O			L				L					L		?	O		
						L											O			L				L					L		?	O		
						L											O			L				L					L		?	O		
						L											O			L				L					L	O	?	O		
			Liasicus	Laqueus		L											O		O	L				L					L	O	O			
						L											O		O	L				L					L	O	O			
						L											O		O	L				L					L	O	O			
						L											O		O	L				L					L	O	O			
				Portlocki		L											O		O	L				L					L	O				
						L											O		O	L				L				O	L	O				
						L											O		O	L				L				O	L	O				
						L											O		O	L				L				O	L	O				
			Planorbis	Johnstoni		L										X	X		X	X			X	L	X	X	X	O	L	O				
						L										X	X		X	X			X	L	X	X	X	O	L					
					JF1	L										X	X			X			O	L	X									
						L										X				X			O	L	X									
				Planorbis		X										X				X			O	L	X									
						X										X			X	X			O	L	X									
						X		X								X	X		X	X	X		O	L	X									
						X		X								X	X		X	X	X		O	L										
						X										X			X	X	X		O	L										
						X										X			X	X	X	X												
						X										X			X	X	X	X												
						X										X			X	X	X													
						X		X								X			X	X														
						X		X								X			X															
PENARTH	Lilstock	Langport				X		X					X			X	X	X	X															
					Eoguttulina liassica Assemblage	X		X				X	X			X	X	X																
						X										X																		
						X																												
						X										X	X																	
						X																												
		Cotham			*Glomospira / Glomospirella* Assemblage		X			X	X		?		X																			
							X			X	X																							
							X			X																								
							X			X		X																						
							X		X	X		X																						
							X		X	X		X	X	X	X																			
	Westbury						X					X	X																					
							X					X																						
							X		X	X	X	X																						
							X		X	X	X	X																						
							X																											
MMG	Blue Anchor						X	X																										
							X	X																										
						?	X	X																										
					?																													

Figure 8. Foraminifera from the Blue Anchor Formation to Blue Lias Formation succession at St Audrie's Bay, Doniford Bay, and other west Somerset coast and eastern Bristol Channel localities

Sources: Copestake (1989): **X** - record. Copestake and Johnson (1989): **O** - record from eastern Bristol Channel sections including St Audrie's Bay and other west Somerset localities; *L* - summary (unlocalised) ranges of long-ranging taxa; **?** - uncertain records

Abbreviation: MMG – Mercia Mudstone Group.

Green lines - separation of foraminifer assemblage and zonal units

Red lines - separation of ammonite zones and subzones

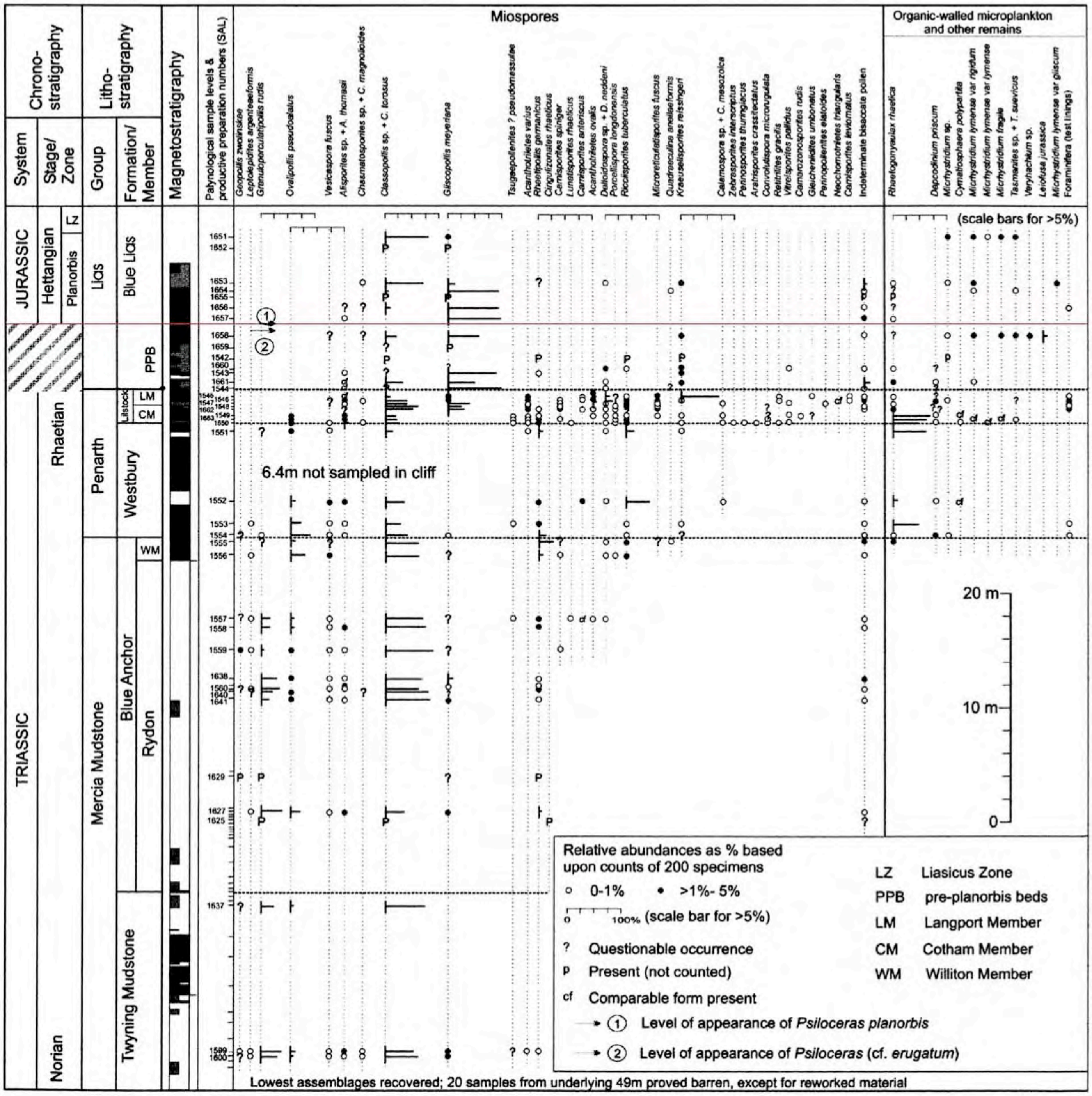
GROUP	Formation	Member	Ammonite zones	Cypridacea indet.	*Cytherelloidea* sp.	*Ogmoconchella aspinata*	*Bairdia* sp.	*Paradoxostoma pusillum*	*Ogmoconchella* sp.	*Polycope* sp.	*Nanacythere* sp.	*Polycope cerasia*	*Ektyphocythere translucens*	*Ogmoconcha hagenowi*	*Darwinula* sp.	*Ogmoconchella bristolensis*	*Cytherella* sp.	*Isobythocypris* sp.	*Ektyphocythere* sp.	*Cytherella plattensis*	*Eucytherura sagitta*	*Eucytherura minor*	*Cytherelloidea praepulchella*
LIAS	Blue Lias		aZ	C																			
				C		C					C	C	C	C									
						LB																	
			liZ	C		C		C	C	C													
						LB																	
			pZ			W					W												
				C		C																	
				LB			LB																
					L														L	L			
				L	L											?L			L				
													W										
																	W	W					
				W	W												W						
PENARTH	Lilstock	Langport														S				S	S	S	S
																?L							
					W											? W	W						
				W											W								
				LB																			
		Cotham			LB	LB																	
	Westbury			LB																			

Figure 9. Ostracods from the Penarth Group and Blue Lias Formation at St Audrie's Bay, Doniford Bay, and other west Somerset coast localities

Sources: C – St Audrie's Bay (Lord & Boomer, 1990, Appendix, 4), L – Lilstock (Lord & Boomer, 1990, Appendix, 5), LB – St Audrie's Bay (Lord & Boomer, 1990, Appendix, 3), S – Warren Bay (Swift, 2003), W – Watchet (Lord & Boomer, 1990, Appendix, 2).

Abbreviations: aZ – Angulata Zone, liZ – Liasicus Zone, pZ – Planorbis Zone; (red lines - separation of ammonite zones)

Figure 10


Chronostratigraphy
System
Stage/Zone
Lithostratigraphy
Group
Formation/Member
Magnetostratigraphy
Palynological sample levels & productive preparation numbers (SAL)
Miospores
Organic-walled microplankton and other remains
JURASSIC
Hettangian
Planorbis
LZ
TRIASSIC
Rhaetian
Norian
Lias
Blue Lias
PPB
Penarth
Lilstock
LM
CM
Westbury
Mercia Mudstone
WM
Blue Anchor
Rydon
Twyning Mudstone
Geopollis zwolinskae
Leptolepidites argenteaeformis
Granuloperculatipollis rudis
Ovalipollis pseudoalatus
Vesicaspora fuscus
Alisporites sp. + A. thomasii
Chasmatosporites sp. + C. magnolioides
Classopollis sp. + C. torosus
Gliscopollis meyeriana
Tsugaepollenites ? pseudomassulae
Acanthotriletes varius
Rhaetipollis germanicus
Cingulizonates rhaeticus
Carnisporites spiniger
Lunatisporites rhaeticus
Carnisporites anteriscus
Acanthotriletes ovalis
Deltoidospora sp. + D. neddeni
Porcellispora longdonensis
Ricciisporites tuberculatus
Microreticulatisporites fuscus
Quadraeculina anellaeformis
Kraeuselisporites reissingeri
Calamospora sp. + C. mesozoica
Zebrasporites interscriptus
Perinosporites thuringiacus
Aratrisporites crassitectatus
Convolutispora microrugulata
Retitriletes gracilis
Vitreisporites pallidus
Camarozonosporites rudis
Gleicheniidites umbonatus
Perinopollenites elatoides
Neochomotriletes triangularis
Carnisporites leviornatus
Indeterminate bisaccate pollen
Rhaetogonyaulax rhaetica
Dapcodinium priscum
Micrhystridium sp.
Cymatiosphaera polypartita
Micrhystridium lymense var rigidum
Micrhystridium lymense var lymense
Micrhystridium fragile
Tasmanites sp. + T. suevicus
Veryhachium sp.
Leiofusa jurassica
Micrhystridium lymense var gliscum
Foraminifera (test linings)
(scale bars for >5%)
1651
1652
1653
1654
1655
1656
1657
1658
1659
1542
1660
1543
1661
1544
1546
1547
1548
1662
1549
1663
1550
1551
1552
1553
1554
1555
1556
1557
1558
1559
1638
1560
1639
1640
1641
1629
1627
1625
1637
1599
1600
①
②
6.4m not sampled in cliff
20 m
10 m
0
Relative abundances as % based upon counts of 200 specimens
○ 0-1%
● >1%- 5%
0 100% (scale bar for >5%)
? Questionable occurrence
P Present (not counted)
cf Comparable form present
→ ① Level of appearance of Psiloceras planorbis
→ ② Level of appearance of Psiloceras (cf. erugatum)
LZ Liasicus Zone
PPB pre-planorbis beds
LM Langport Member
CM Cotham Member
WM Williton Member
Lowest assemblages recovered; 20 samples from underlying 49m proved barren, except for reworked material

GROUP	Formation	Member	Bed number	Level in formation (m)		Spore taxa		Non-spore taxa		All miospore taxa	
				Below top	Above base	Genera	Species	Genera	Species	Genera	Species
LIAS	Blue Lias		37		12.86			3	3	3	3
			36		11.94			2	2	2	2
			24		8.97	2	2	4	3	6	5
					8.36			3	3	3	3
					7.83			2	2	2	2
			17-19		6.84			4	2	4	2
			13-15		5.92			2	2	2	2
			7		4.63	1	1	2	2	3	3
					3.56			2	1	2	1
			5		2.6			4	4	4	4
			3		1.66			1	1	1	1
			1		1.23	2	2	6	5	8	7
					0.51	2	2	3	1	5	3
					0.01	1	1	3	1	4	2
PENARTH	Lilstock	Langport			2.36-2.67	7	7	4	3	11	10
					2.13	9	10	7	6	16	16
					1.98	4	6	6	5	10	11
		Cotham			1.68	5	7	4	3	9	10
					1.37	5	6	4	3	9	9
					0.76	11	10	7	7	18	17
					0.51	3	3	7	6	10	9
					0.23	11	10	11	9	22	19
	Westbury			0.61		3	3	6	5	9	8
		Sample gap (6.4m)									
					3.2	6	3	6	6	12	9
					1.07	2	2	7	7	9	9
					0.31			8	8	8	8
MERCIA MUDSTONE	Blue Anchor	Williton		0.46		1	1	5	5	6	6
				1.6		4	5	5	5	9	10
		Rydon		7.01		4	3	8	8	12	11
				7.9				6	6	6	6
				9.75		2	2	6	6	8	8
				12.29				7	7	7	7
				13.11		2	1	9	7	11	8
				13.16				8	5	8	5
				14.02				8	7	8	7
				20.73				3	3	3	3
				23.93		1	1	7	7	8	8
				24.61		1	1	2	2	3	3
	BMF			0.91				4	3	4	3
				13.61		2	2	10	9	12	11
				14.02		1	1	7	7	8	8

Figure 11. Numbers of genera and species in spore, non-spore and total miospore associations from the upper Branscombe Mudstone Formation to lower Blue Lias Formation succession at St Audrie's Bay

Source: Warrington (ms records).

Numbers: 1 to 4 | 5 to 9 | > 9

– · – · – level of erosion surface overlying deformed beds in the Cotham Member.

Abbreviation: BMF - Branscombe Mudstone Formation

Red line – candidate Hettangian GSSP level

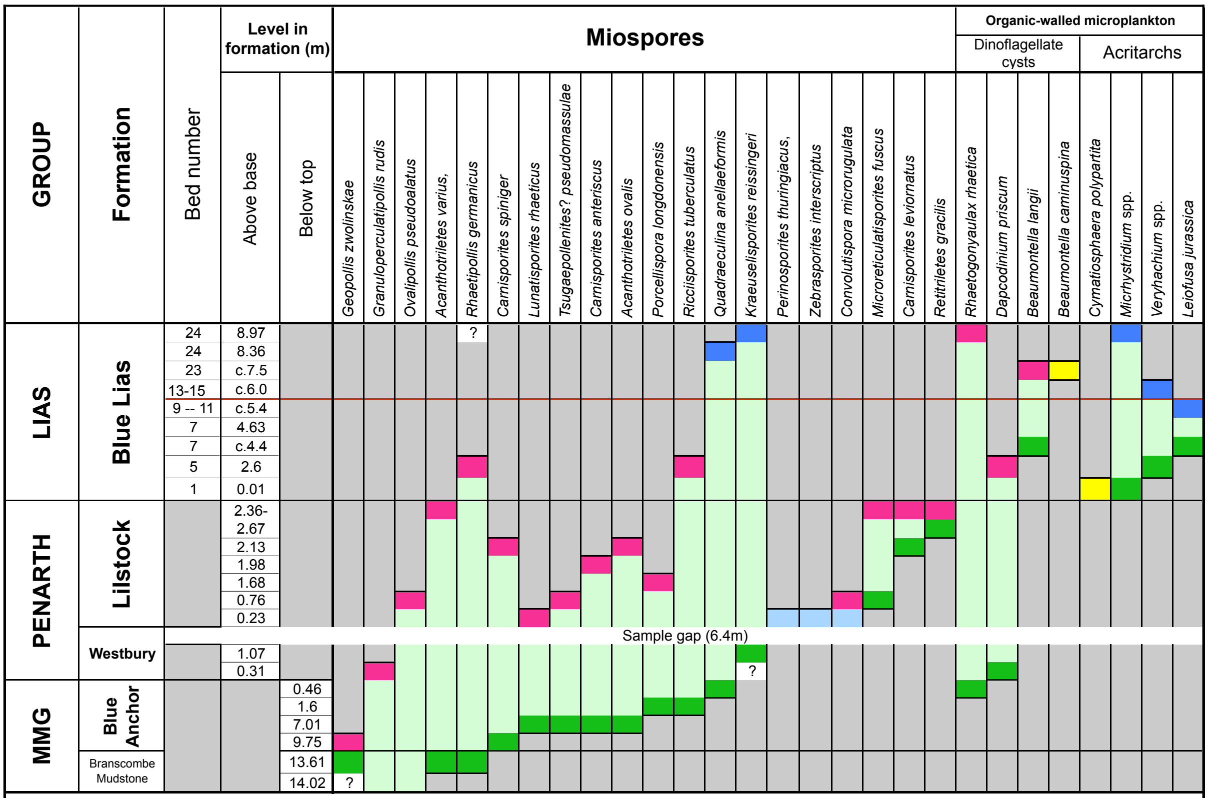
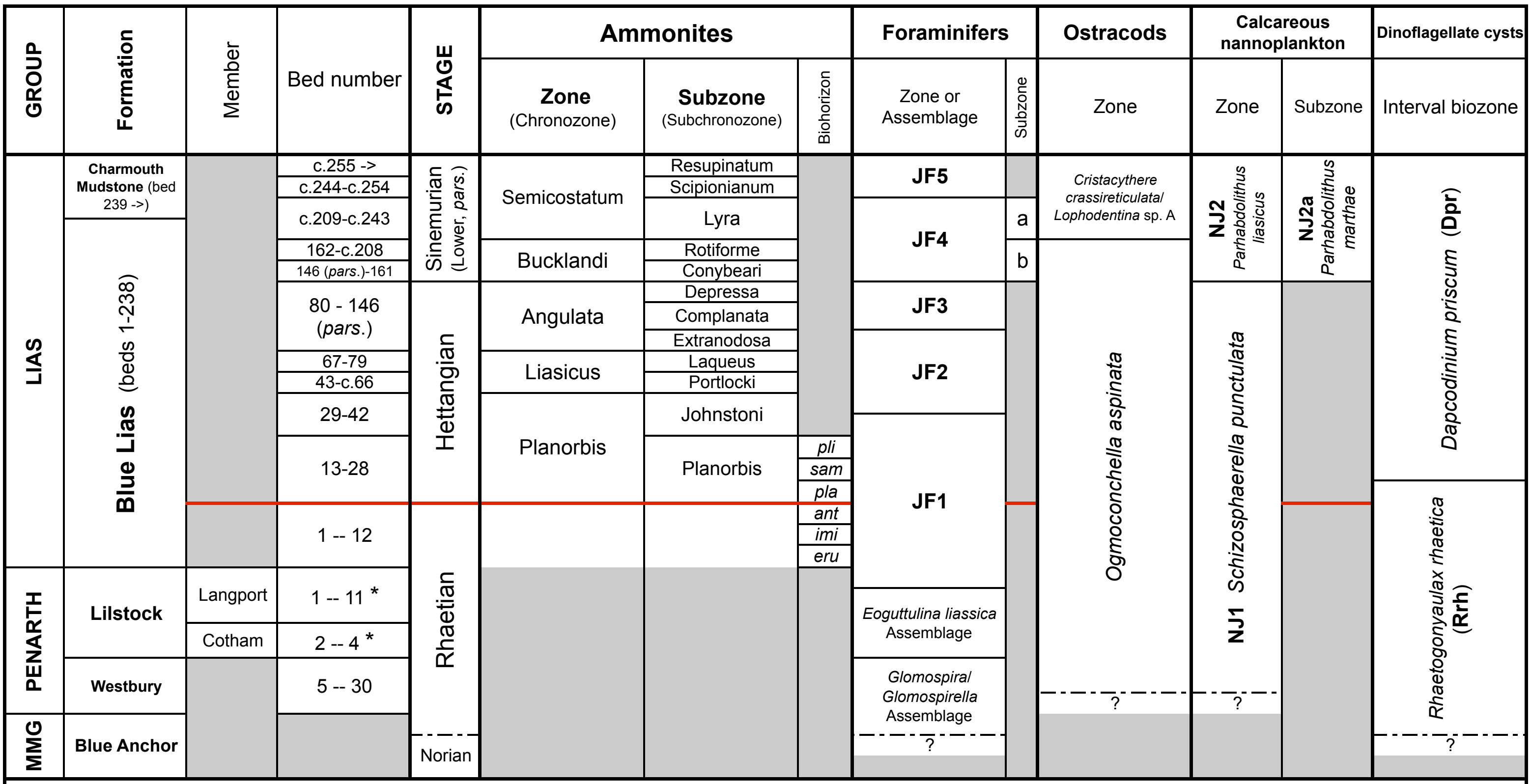


Figure 12. First and last occurrences of selected palynomorphs in the Branscombe Mudstone Formation to Blue Lias Formation succession at St Audrie's Bay

Source: Warrington, *in* Hounslow *et al*., 2004, fig. 5

Key:		
	🟩	Level of first definite record in this section
	🟥	Level of last definite record in this section
	▨	Recorded above gap in sampling (may appear within that interval)
	🟨	Solitary record in this section
	🟦	Highest record in this section but known from higher levels elsewhere
	?	Uncertain first or last records in this section

Red line – candidate Hettangian GSSP level.



GROUP	Formation	Member	Bed number	STAGE	Ammonites			Foraminifers		Ostracods	Calcareous nannoplankton		Dinoflagellate cysts
					Zone (Chronozone)	Subzone (Subchronozone)	Biohorizon	Zone or Assemblage	Subzone	Zone	Zone	Subzone	Interval biozone
LIAS	Charmouth Mudstone (bed 239 ->)		c.255 ->	Sinemurian (Lower, *pars.*)	Semicostatum	Resupinatum		JF5		*Cristacythere crassireticulata*/ *Lophodentina* sp. A	NJ2 *Parhabdolithus liasicus*	NJ2a *Parhabdolithus marthae*	*Dapcodinium priscum* (Dpr)
			c.244-c.254			Scipionianum							
	Blue Lias (beds 1-238)		c.209-c.243			Lyra		JF4	a				
			162-c.208		Bucklandi	Rotiforme			b	*Ogmoconchella aspinata*			
			146 (*pars.*)-161			Conybeari							
			80 - 146 (*pars.*)	Hettangian	Angulata	Depressa Complanata Extranodosa		JF3			NJ1 *Schizosphaerella punctulata*		
			67-79		Liasicus	Laqueus		JF2					
			43-c.66			Portlocki							
			29-42		Planorbis	Johnstoni		JF1					
			13-28			Planorbis	*pli* *sam* *pla*						
			1 -- 12	Rhaetian			*ant* *imi* *eru*						*Rhaetogonyaulax rhaetica* (Rrh)
PENARTH	Lilstock	Langport	1 -- 11 *					*Eoguttulina liassica* Assemblage					
		Cotham	2 -- 4 *										
	Westbury		5 -- 30					*Glomospira*/ *Glomospirella* Assemblage		?	?		
MMG	Blue Anchor			Norian				?					?

Figure 13. Biostratigraphic schemes applicable to the Blue Anchor Formation to Charmouth Mudstone Formation succession at St Audrie's Bay and Doniford Bay

Sources: Ammonites (Zone/Subzone - Ivimey-Cook & Donovan, 1983, Page, 2005; Biohorizon - Page & Bloos, 1998; Page, 2005). Foraminifers (Copestake, 1989; Copestake & Johnson, 1989). Ostracods (Boomer, 1991). Calcareous nannoplankton (Bown, 1998b; Bown & Cooper, 1998). Dinoflagellate cysts (Powell, 1992b; Riding & Thomas, 1992). Bed numbers from Whittaker and Green (1983), with * after Richardson (1911).

Ammonite biohorizons: *eru – erugatum*, *imi – imitans*, *ant – antecedens*, *pla – planorbis*, *sam – sampsoni*, *pli - plicatulum*

Abbreviations: MMG – Mercia Mudstone Group

Red line – candidate Hettangian GSSP level.

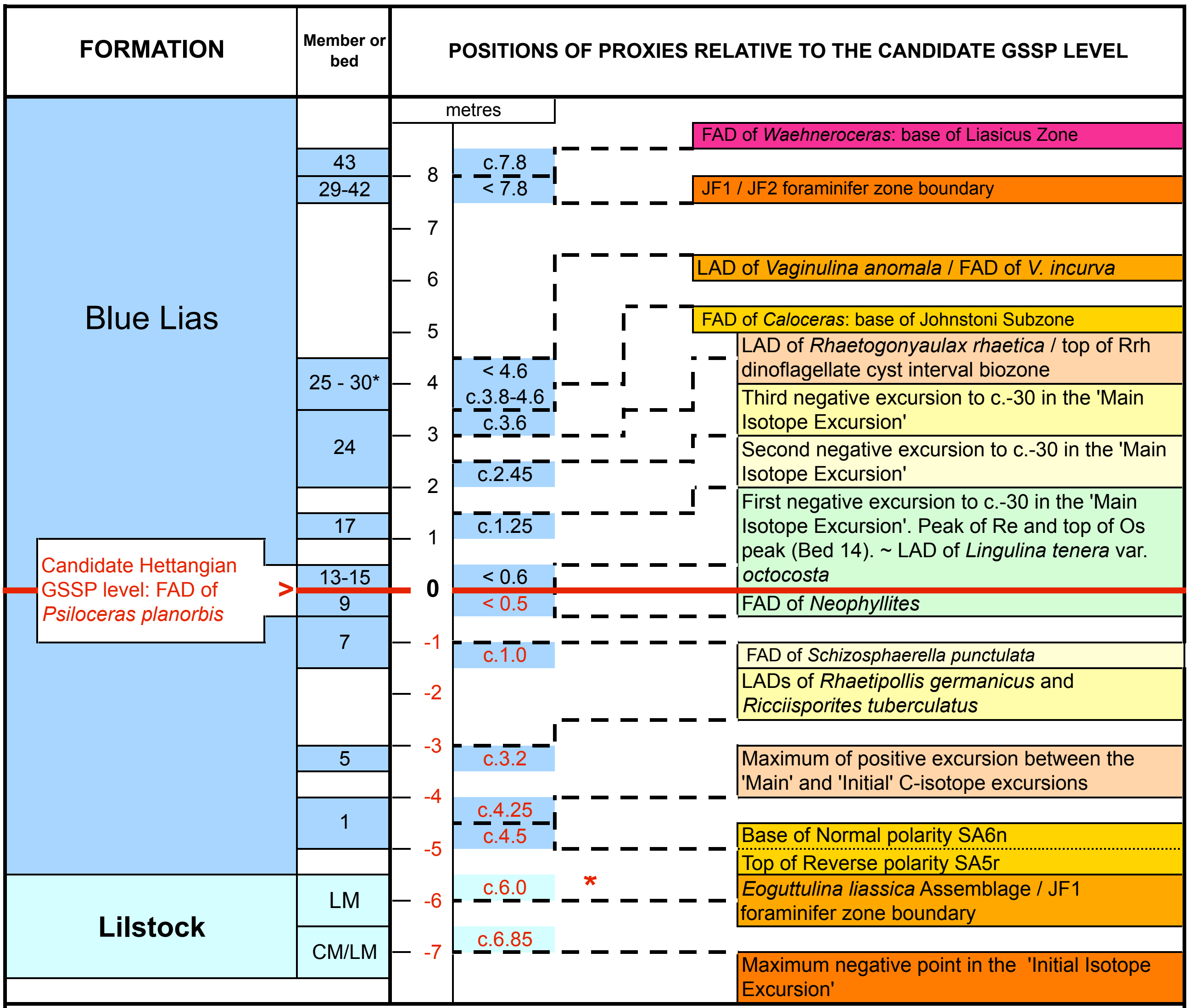


Figure 14. Proxies for the candidate Hettangian GSSP in the St Audrie's Bay section

* Approximate level of nearest occurrences of conodonts (see 6.2.3)

* Base of Johnstoni Subzone: bed 25 (Page, 2005) (Fig. 5), bed 29 (Ivimey-Cook & Donovan, 1983) or bed 30 (Whittaker & Green, 1983) (13.2.3.c; see **18**)

LM - Langport Member; CM/LM - approximate level of Cotham Member / Langport Member boundary

SELECTION AND VOTING PROCEDURES FOR THE BASE HETTANGIAN

INTRODUCTION

Nicol MORTON

The problem of defining the base of the Jurassic by a GSSP/ASSP has been one of the most difficult to resolve that I have personally come across. I have, as Chairman of the Jurassic Subcommission, and therefore voting member of the International Commission on Stratigraphy, seen a large array of GSSP proposals during the last eight years. Many were the best available on the basis of currently available information; others were very convincing; a few were, to put it politely, questionable but with no clear alternative, so were supported. This one, on the base of the Hettangian/Jurassic, is by far the most complex that I have come across - so many possibilities, so few details, so many unknowns!

The problem of defining the Triassic/Jurassic boundary has been investigated for many years, but the research has been especially active in the last seven years or so with the parallel activities of the Triassic/Jurassic Boundary Working Group of the Jurassic Subcommission and of the IGCP Project 458 on Triassic-Jurassic Boundary Events, both of which have contributed enormous amount of new information. Much of the membership was common to both.

For decades it was accepted generally that the base of the Jurassic should be identified with the first appearance of "typically Jurassic" ammonites and especially the genus *Psiloceras*. The oldest known at that time was *Psiloceras planorbis* and this species, and the Planorbis Zone to which it gave its name, was best known in south-west England. Even though no Triassic ammonoids are known from this area, it was generally assumed that these were the oldest "Jurassic" ammonites. Definition of the base of the Jurassic on this basis remains one option, and favoured by some. However, more recent research has shown that older species of *Psiloceras*, in Britain but more especially elsewhere, exist, stratigraphically above Triassic ammonoids. This was first demonstrated in Nevada, then more recently elsewhere (e.g. Chile, Tibet, Austria).

The question to be answered was whether the base of the Jurassic should be based on these older species of *Psiloceras* or remain with the traditional basis of *Psiloceras planorbis*. In the meantime other possibilities for the definition were proposed, namely a major turnover of radiolarian faunas or a carbon-isotope excursion. These were the choices faced by the Triassic/Jurassic Boundary Working Group, as explained in the "Foreword" document.

It was never likely that, given the controversies, there would be unanimous approval of any conclusion. So it has transpired - there remain strongly entrenched, and justifiable, dissenting opinions. Some cannot accept that their personal preference was not successful and are not happy with the final result. Others think that a decision is premature, though when and how further data could become available in the future to enable a better decision is not at all evident. Of course, not all problems have been resolved and there remains work to be done, but the result is considered by most as giving an acceptable definition of this difficult boundary.

In the end, after many discussions by email and other means, the decision was made by at least a two-thirds majority for the Kuhjoch section in Austria to be proposed as GSSP together with the Ferguson Hill section in Nevada, USA as ASSP. The two are complementary and although there are two separate proposal documents because of the circumstances of separate authorship, they are considered by the Jurassic Subcommission as constituting a single proposal.

FOREWORD

Nicol Morton, Chairman ISJS
Geoffrey Warrington, Convenor TJBWG
Gert Bloos, Secretary TJBWG

This document has been prepared to explain the background and procedures followed by members of the Triassic/Jurassic Boundary Working Group (TJBWG) for selection of the preferred GSSP for the base of the Hettangian Stage and the Jurassic System. It is intended to be a factual account of what happened and to give a reasonably objective account of why the voting went as it did, so that this proposal can be scrutinized objectively. It has some minor revisions from the document submitted to the Jurassic Subcommission.

Background

The basal boundary of the Jurassic has been a long-lasting problem, illustrated for example by the status of the Rhaetian Stage, variously placed in the Triassic or Jurassic, until international agreement was reached to include it as the final stage of the Triassic. The Triassic/Jurassic boundary interval was the time of one of the major evolutionary crises in Earth history, and one that has proved to be complex. It was also a time of active plate tectonics during early stages of the breakup of Pangaea (and therefore rapidly changing palaeogeography), of a major volcanic phase (Central Atlantic Magmatic Province) and apparent major changes of sea-level in many areas, possibly global. This last event resulted in there being very few areas where a continuous sequence of strata across the boundary is preserved.

The Jurassic Subcommission established a Working Group, led by the late René MOUTERDE (France) succeeded by Geoffrey WARRINGTON (UK), to research and eventually propose definition of the boundary at a stratotype (GSSP). More recently, IGCP Project 458 on Triassic/Jurassic Boundary Events, now completed, was set up with leaders Stephen HESSELBO (UK), Christopher McROBERTS (USA) and Jozsef PALFY (Hungary). Both groups contributed a large amount of new data and ideas on the Triassic/Jurassic boundary interval.

By 2003 the Triassic/Jurassic Boundary Working Group (TJBWG) had identified and compared four sections with continuous sedimentation and marine faunas across the boundary interval – St. Audrie's Bay (SW England), New York Canyon (Nevada), Kunga Island (western Canada) and Chilingote (Peru), but no favoured candidate emerged. Subsequently, two new sections were discovered and proposed as candidates – Kuhjoch (Austria) in 2005, and Waterloo Bay (Northern Ireland) in 2006. Also, a broader range of markers was proposed, including radiolarians and a carbon isotope excursion in addition to ammonites. In September 2006, the 7th International Congress on the Jurassic System, held in Krakow (Poland), enabled discussion of the various proposals; during this the candidature of Chilingote (Peru) was withdrawn.

Candidate sections

In 2007 the following proposals were formally submitted to the members of the TJBWG for comparison, discussion and, eventually, selection:

(a) Ferguson Hill section, New York Canyon, Nevada, USA

By S.G. LUCAS, D.G. TAYLOR, J. GUEX, L.H. TANNER and K. KRAINER
with primary marker the ammonite *Psiloceras spelae*.

(b) Ferguson Hill section, New York Canyon, Nevada, USA

By C.A. McROBERTS, P.D. WARD and S.P. HESSELBO
with primary marker a carbon isotope excursion.

(c) Kuhjoch section, Karwendel Mountains, Northern Calcareous Alps, Tyrol, Austria

By A. von HILLEBRANDT, L. KRYSTYN, W.M. KUERSCHNER (with contributions by P.R. BOWN, C. McROBERTS, M. RUHL, M. SIMMS, A. TOMASOVYCH and M. URLICHS)
with primary marker the ammonite *Psiloceras* cf. *spelae*.

(d) Kunga Island section, Queen Charlotte Islands, British Columbia, Canada

By L.M. LONGRIDGE, E.S. CARTER, J.W. HAGGART and P.L. SMITH with primary marker a major evolutionary change of radiolarian faunas.

(e) St. Audrie's Bay section, Somerset, England, UK

By G. WARRINGTON, J.C.W. COPE and H.C. IVIMEY-COOK

with primary marker the ammonite *Psiloceras planorbis*.

(f) Waterloo Bay section, Larne, Northern Ireland, UK

By M.J. SIMMS and A.J. JERAM

with primary marker the ammonite *Psiloceras planorbis*.

All except the second last were published electronically in the International Subcommission on Jurassic Stratigraphy Newsletter no. 34, part 1. The St. Audrie's Bay proposal is published herein. They can be downloaded freely from the new Jurassic Subcommission website at:

http://jurassic.earth.ox.ac.uk

The quality of the science in all these proposals is very impressive and all the authors are to be congratulated on their work.

Selection and voting

In view of the large number of proposed sections and primary markers, the membership of the TJBWG was enlarged by the Convenor and Secretary in consultation with the Subcommission Chairman. All who were known to have an interest and input were invited to participate, to make the Group as representative as possible so that any decisions reached would carry authority. (For a list of those who accepted the invitation see ISJS Newsletter 34,1.) To enable discussions, a special password-protected website was established by Christopher McROBERTS, containing the full proposal documents and with facilities to enable TJBWG members to post discussions on the various topics. In the final weeks of the selection processes there was also a huge amount of constructive discussion and exchanges by emails circulated to all WG members.

The selection procedures were organised by the Secretary of the TJBWG in consultation with the Subcommission Chairman. The Convenor withdrew from these in view of his involvement with one of the proposals. Voting was carried out in three stages:

1. Selection of the primary marker

Voting form issued 14th February 2008; response deadline 29 February 2008.

Four different markers were proposed:

(a) A carbon isotope negative excursion identified in several sections; this is the lowest stratigraphically and would have placed some strata traditionally regarded as Triassic in the Jurassic;

(b) A major evolutionary turnover in the radiolarian faunas, slightly predating the first appearance of ammonites traditionally regarded as Jurassic;

(c) The first appearance of the ammonite genus *Psiloceras*, traditionally regarded as the oldest "Jurassic" ammonite, represented by the species *Psiloceras spelae*;

(d) The first appearance of the ammonite *Psiloceras planorbis*, for many decades regarded as the oldest (then known) Jurassic ammonite and index of the Planorbis Zone as basal zone of the Hettangian; this would have placed the boundary at the highest of the levels proposed.

Voting:

Number of TJBWG members = 75

Returned voting forms (all valid) = 67 (89.3%).

(i) for Psiloceras spelae / cf. ***spelae***

[Jean Guex and Axel von Hillebrandt agreed that the Ferguson Hill and Kuhjoch ammonites represent the same species, with minor population differences at subspecies level, and concluded that they were contemporaneous within acceptable limits of resolution.]

votes for = 36 (53.7%)

Guex, Lucas, Pienkowski, Kozur, Krystyn, Hillebrandt, Michalik, Meister, Blau, Aberhan, Tanner, Bucher, Hallam, Korte, Yin, Siblik, Urlichs, Haas, Furrer, Bartolini, Bloos, Lathuillere, Tomasovych, Kürschner, Feist-Burkhardt, Vörös, Götz, Page, Vuks, Lindström, Sha, Polubotko, Repin, Hesselbo, Enay, Menning.

(ii) for Psiloceras planorbis

votes for = 13 (19.4%)

Cope, Simms, Hounslow, Stevens, Prinz-Grimm, Warrington, Hall, Ivimey-Cook, Donovan, Jeram, Riccardi, Mancenido, Damborenea.

(iii) for Carbon Isotope Excursion
votes for = 11 (16.4%)
Ward, Olsen, Lord, McRoberts, Cohen, Coe, Bown, Ciarapica, Smith, Longridge, Stanley.

(iv) for Radiolarian faunal turnover
votes for = 7 (10.5%)
Ruckwied, Hirsch, Matsuoka, Hori, Palfy, Carter, Herngreen.

2. Selection of the preferred section

Voting form issued 6 March 2008; response deadline 17 March 2008.

Following the voting, the primary marker chosen by a majority of the TJBWG members was the ammonite *Psiloceras spelae*, which had been proposed and could be recognised in only two candidate sections – Kuhjoch section (Austria) and Ferguson Hill section (USA). The second stage ballot offered a choice between these two candidate sections.

Number of TJBWG members = 75
Returned voting forms (all valid) = 57 (76.0%)

(i) for Kuhjoch section, Austria
votes for = 32 (56.1%)
Hillebrandt, Pienkowski, Aberhan, Feist-Burkhardt, Vörös, Blau, Hounslow, Hallam, Menning, Yin, Meister, Bown, Page, Siblik, Cope, Boomer, Bloos, Michalik, Olsen, Stevens, Haas, Vuks, Repin, Polubotko, Hesselbo, Tomasovych, Longridge, Hall, Furrer, Kürschner, Urlichs, Krystyn.

(ii) for Ferguson Hill section, USA
votes for = 18 (31.6%)
Guex, Lucas, Hirsch, Lord, Matsuoka, McRoberts, Carter, Ruckwied, Korte, Kozur, Götz, Taylor, Hori, Ciarapica, Sha, Mancenido, Enay, Lindström.

(iii) abstain
votes for = 7 (12.3%)
Warrington, Palfy, Riccardi, Damborenea, Ivimey-Cook, Jeram, Smith.

3. Confirmation of majority vote

Voting form issued 19 March 2008; response deadline 7 April 2008.

The majority vote for the Kuhjoch section as preferred GSSP candidate did not achieve the required 60% majority of the votes cast. Therefore, a further ballot was held to seek the approval of TJBWG members for this section to be proposed to the Jurassic Subcommission.

Number of TJBWG members = 75
Returned voting forms (all valid) = 61 (81.3%)

(i) **YES** votes = 48 (78.7%)
Guex, Vuks, Polubotko, Repin, Kürschner, Prinz-Grimm, Stanley, Menning, Hounslow, Bloos, Simms, Pienkowski, Yin, Hallam, McRoberts, Hillebrandt, Korte, Bartolini, Donovan, Tomasovych, Hesselbo, Enay, Stevens, Meister, Haas, Cope, Aberhan, Michalik, Krystyn, Smith, Hall, Herngreen, Boomer, Olsen, Vörös, Longridge, Tanner, Lindström, Furrer, Lathuilière, Feist-Burkhardt, Urlichs, Blau, Götz, Siblik, Gazdzicki, Ruckwied, Bown.

(ii) **NO** votes = 6 (9.8%)
Damborenea, Mancenido, Warrington, Hori, Ward, Palfy.

(iii) **ABSTAIN** votes = 7 (11.5%)
Kozur, Jeram, Matsuoka, Hirsch, Carter, Ivimey-Cook, Riccardi.

At the same time a ballot was held to ask TJBWG members opinions of a suggestion to propose the Ferguson Hill section as auxiliary stratotype (ASSP).

Number of TJBWG members = 75
Returned voting forms (all valid) = 57 (76.0%)

(iv) **YES** votes = 35 (61.4%)
Guex, Vuks, Polubotko, Repin, Stanley, Menning, Bloos, Pienkowski, Hallam, Hillebrandt, Bartolini, Donovan, Tomasovych, Enay, Kozur, Stevens, Haas, Cope, Aberhan, Michalik, Smith, Hall, Korte, Hori, Herngren, Boomer, Longridge, Tanner, Lindström, Furrer, Hirsch, Carter, Blau, Götz, Ruckwied

(v) **NO** votes = 9 (15.8%) Kürschner, Hounslow, Simms, McRoberts, Hesselbo, Warrington, Olsen, Lathuilière, Palfy

(vi) **ABSTAIN** votes = 13 (22.8%) Damborenea, Prinz-Grimm, Yin, Mancenido, Meister, Krystyn, Jeram, Matsuoka, Vörös, Feist-Burkhardt, Gazdzicki, Riccardi, Bown

Conclusion

The Kuhjoch section, Karwendel Mts, Northern Calcareous Alps, Austria, has been accepted by vote of the members of the TJBWG to be proposed as GSSP for the base of the Hettangian Stage and the Jurassic System. The Ferguson Hill section, New York Canyon, Nevada, USA has been accepted by vote to be proposed as ASSP; an integrated proposal must be prepared for later submission to the Jurassic Subcommission. and to the International Commission on Stratigraphy.

Comments on the result of the votes

This comment does not repeat or evaluate the arguments on the different candidate GSSPs, their boundary definitions and correlation potential, but considers only some general aspects.

The focus of investigation and of discussion was on the boundary itself. Only those sections that have continuous sedimentation and succession of sufficiently preserved fossils through the boundary interval could be considered as candidate GSSPs. Our search for such sections revealed that they are rather rare. Most sections shows deficiencies of one or other kind so that the boundary cannot be recognized.

It is important that even if the boundary itself is not recognizable itself, the ages of the rocks above and below the boundary can be recognized unequivocally. This was the case with traditional boundary levels used in the past, although they have turned out to differ in age, more or less. However, one common characteristic was that the ranges of *Choristoceras marshi*, *Ch. crickmayi* and the conodont *Misikella posthernsteini*, were regarded as latest Triassic, while *Psiloceras* was regarded as earliest Jurassic wherever found in the world. In complete sections these ranges are separated by an intermediate interval where time-diagnostic fossils are essentially lacking. Thus, an overlap of index fossils of latest Triassic and earliest Jurassic is excluded. Rare exceptions, such as *Choristoceras minutum* or the late conodont "*Neohindeodella*" *detrei* offer no difficulty because these species are known only from sediments above the ranges of the accepted latest Triassic index species. A boundary level at the appearance of *Psiloceras spelae* is situated between the ranges of the two groups of age-diagnostic fossils referred to above and in this respect continues historical stratigraphical usage.

On the other hand, if the boundary had been placed at a lower level, this would separate the stratigraphic range of, for example, *Misikella posthernsteini* into a Triassic part and a Jurassic part. Consequently, this important index fossil would lose its unequivocal age-diagnostic character distinguishing latest Triassic from earliest Jurassic.

Similarly, a boundary at a higher level defined by a species within the psiloceratid succession could be correlated only within the faunal province where the GSSP is situated; not all psiloceratids would be Jurassic. In other faunal provinces with different ammonite sequences, only tentative correlations would be possible and stratigraphic allocation of new, hitherto unknown, psiloceratids would remain uncertain.

The investigations of the TJBWG have yielded results that are certainly significant beyond the primary aim, the selection of a GSSP for the base of the Jurassic. Each candidate section will remain an important international stratigraphical reference in the future contributing to the elucidation of a very special important time-span in the history of Earth. Some open questions remain and new ones arise; therefore, investigations must be continued, as indicated below.

Remarks on the Triassic/Jurassic transitional boundary interval

This is essentially an attempt to integrate the results from the six candidate GSSP proposals into an idea on what happened at the end of the Triassic as now understood and where in this history the T-J boundary is defined. The primary causes of the environmental changes across the T-J boundary are not discussed here because they are not yet sufficiently known.

For a long time the late Rhaetian was known as a period of decreasing diversity in important fossil groups, such as ammonoids, bivalves, brachiopods, conodonts, ostracodes, and foraminifers. The immediate transition into the Jurassic, however, was generally obscure, for various reasons. The end-Triassic sea level changes caused regionally widespread gaps in sedimentation and breaks of facies sequence. Moreover, unfavourable facies caused poor records of fossils with regard to frequency, diversity and preservation. Additionally, subsequent influences such as diagenetic processes and thermal metamorphism changed or even deleted biotic and non-biotic signals.

The time of decline in the late Rhaetian ended in a major crisis for the fossil groups referred to above, with a final interval characterized by a minimum of frequency and diversity. It is remarkable that not only the groups mentioned above as being in decline were affected but so also were radiolarians, whose diversity (against the general negative trend) still increased up to the beginning of the final crisis.

Most probably the beginning of the final crisis is indicated by the strikingly rapid extinction of about 70 Triassic species of radiolarians (which were still present in bed 9 of Kunga Island; 57 of them are missing already in bed 10, while 13 short-lived holdovers are absent in bed 13; Longridge et al. 2007 *ISJS Newsletter* 34(1): 21-33, fig. 4). Only three Triassic species persisted above the extinction level. From bed 10 upwards 20 new species appeared. Thus there was minimal overlap of the earlier and later groups.

There can be little doubt that this turnover reflects a major environmental change. To find out the reason, it seems important that the radiolarians are a pelagic group. Important also is that genera with highly specialised morphology were most concerned. Such forms obviously were adapted to a specialised mode of life that could not be continued after the environmental change. Since calcareous nannoplankton were also concerned it may be that the symbiotic algae were the particularly sensitive element in the radiolarians.

According to Williford et al. (2007 *PPP* 244: 290-296. fig. 1) the radiolarian turnover is situated within the initial negative Carbon Isotope Excursion (CIE) at Kennecott Point which has a range of about 4 m (110-114 m). Therefore it seems rather probable that the extinction of Triassic radiolarians and the CIE reflect the same environmental change and that this change was the reason for at least the beginning of the final crisis.

Whereas the reaction of the radiolarians to the environmental change was immediate and strong, other latest Triassic fossil groups survived a short time after the CIE. Holdovers into the critical interval are known from the radiolarians (Kunga Island), conodonts (UK), ammonoids (Ferguson Hill: *Choristoceras crickmayi*), foraminifers, ostracodes, palynomorphs (all Kuhjoch). This means that minimum diversity was reached a short time after the beginning of the crisis.

Of the later part of the critical interval little is known from most of the candidate GSSPs. Since the radiolarian change is completely situated within the CIE according to Williford et al. (2007) it seems that the recovery of the radiolarians began earlier than recoveries of other fossil groups. The reappearance of other fossil groups was clearly later than the CIE.

Most information on the upper part of the critical interval is provided at Kuhjoch and other sections in the same basin (Eiberg Basin). The excellent preservation in these sections (aragonite preserved) indicates that the sections offer the original fossil content without later alteration. The sections show that low diversity persisted almost up to the first appearance of *Psiloceras spelae*. Near this level also in other fossil groups new forms appeared: ostracodes, aragonitic forams, and palynomorphs.

The increase of diversity around the level of *Psiloceras spelae* indicates the end of the final crisis. The appearance of *Psiloceras spelae* at this level is not random. It is at the beginning of a general recovery. The T-J boundary is now proposed at this level. With this definition the final crisis is Triassic. The Jurassic begins with the appearance of new forms that persisted into later Jurassic.

Future plans

It is very evident that in a complex situation such as that summarized above, a single reference section, the GSSP, is inadequate. Of course, the GSSP will remain as the ultimate international point of reference for the base of the Jurassic System. However, further thought must be given as to how best to complement the GSSP with other international points of reference. The following are some topics that require further consideration by the TJBWG and the Jurassic Subcommission:

1. The Ferguson Hill section in New York Canyon (Nevada, USA) provides important supporting information to that of the Kuhjoch section, and its proposal as Auxiliary Stratotype Section and Point (ASSP) has been supported by a vote in the TJBWG. A documented case for this must now be prepared.

2. Current research by Jean Guex and colleagues (see Schaltegger et al. 2008 EPSL 267,266-275) in the Utcubamba Valley, Peru, following up earlier research by Axel von Hillebrandt, has confirmed a similar ammonite succession to that in Nevada and Austria and provided U-Pb ages. Consideration should be given as to whether a selected section should be proposed as an additional Auxiliary Stratotype Section and Point (ASSP).

3. The evolutionary faunal turnover of the radiolaria documented especially in the Kunga Island section provides an important "proxy" for recognition of the base Hettangian/Jurassic, and for interpretation of the biological history of the Earth during this time interval. It provides an important international secondary reference point that merits official recognition.

4. The reference sections in western Europe (St. Audrie's Bay, S.W. England, and Waterloo Bay, Northern Ireland) document the earliest *Psiloceras* faunas in a different faunal province. These are also the only sections proposed as candidates where a magnetostratigraphic record appears to be preserved that could enable correlation with the terrestrial record such as that in the Newark Basin and elsewhere. Provided correlation with the GSSP at Kuhjoch, for example using the Carbon Isotope Excursion, can be refined then these sections will also be useful international secondary reference points.

DETAILS OF VOTING ON PROPOSED GSSP AND ASSP FOR THE BASE OF THE HETTANGIAN STAGE AND JURASSIC SYSTEM

Nicol MORTON

After the results of the voting within the Triassic/Jurassic Boundary Working Group became available the intention was to arrange a ballot on a joint proposal for the GSSP in the Kuhjoch section, Austria, and the ASSP in the Ferguson Hill section, Nevada, USA. Both proposals were revised in the light of discussions and comments during the Working Group voting and a “Foreword” document was prepared explaining the procedures followed and results of the Working Group ballots.

In the event the GSSP proposal for the Kuhjoch section was the first to be ready for distribution and voting by the Voting Members of the Jurassic Subcommission. The “Foreword” document followed and was distributed some days later. Finally a revised summary ASSP proposal for the Ferguson Hill section was distributed and voted on. In retrospect these separate distributions caused some confusion and simultaneous distribution would have been preferable. For consideration of and voting on the GSSP and ASSP proposals by the International Commission on Stratigraphy all documents are being distributed simultaneously.

BALLOT OF VOTING MEMBERS ON HETTANGIAN/JURASSIC GSSP AT KUHJOCH SECTION, AUSTRIA

Distribution of proposal – 4 June 2008
Deadline for votes – 30 June 2008

Number of Voting Members = 22
Votes returned = 21 (95.5%)
[Percentages of returned votes given]

YES votes = 14 (66.7%)
Bown, Cecca, Dietl, Fernandez Lopez, Hesselbo, Hillebrandt, Morton, Ogg, Page, Pavia, Sha, Shi, Shurygin, Wierzbowski.

NO votes = 4 (19.0%)
Carter, Damborenea, Hirsch, Warrington.

ABSTAIN = 3 (14.3%)
Palfy, Smith, Yao.

The proposal received over the required 60% majority of the votes cast.

BALLOT OF VOTING MEMBERS ON HETTANGIAN/JURASSIC ASSP AT FERGUSON HILL SECTION, NEVADA, USA

Distribution of proposal – 3 July 2008
Deadline for votes – 3 August 2008

Number of Voting Members = 22
Votes returned = 17 (77.3%)
[Percentages of returned votes given]

YES votes = 14 (82.4%)
Carter, Cecca, Fernandez Lopez, Hillebrandt, Hirsch, Morton, Page, Palfy, Pavia, Sha, Shi, Shurygin, Smith, Wierzbowski.

NO votes = 3 (17.6%)
Damborenea, Hesselbo, Warrington.

ABSTAIN = 0

[No response = 5 (22.7% of Voting Members) Bown, Dietl, Fedan, Ogg, Yao]

The proposal received over 80% of the votes cast over the required 60% majority of the membership of the Subcommission.