A potential global stratotype for the Sinemurian–Pliensbachian boundary (Lower Jurassic), Robin Hood's Bay, UK: ammonite faunas and isotope stratigraphy

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Abstract – A coastal exposure at Wine Haven, Robin Hood's Bay (North Yorkshire, UK) fulfils the criteria for definition as the Global Stratotype Section and Point (GSSP) for the base of the Pliensbachian Stage (Lower Jurassic). This marine sequence was deposited during a long-term transgression and is relatively expanded stratigraphically. A rich fauna of ammonites above and below the boundary interval allows recognition of the *Leptechioceras* gr. *meigeini*, *Paltechioceras aureolum* and *Paltechioceras tardecrescens* horizons of latest Sinemurian age, and the *Bifericeras donovani*, and *Apoderoceras* gr. *aculeatum* horizons of earliest Pliensbachian age. A suitable level for the boundary is characterized by the faunal association of *Bifericeras donovani* Dommergues & Meister and *Apoderoceras* sp. Strontium-isotope stratigraphy, based on analysis of belemnites, yields a calcite $^{87}Sr/^{86}Sr$ ratio for the suggested boundary level of 0.707425 ± 0.000021 (combined uncertainties based on line fit to stratigraphic dataset (± 0.000004) and measurement of the standard (± 0.000017)). Alternative uncertainties of ~ ± 0.000008 are associated with the most extreme interpretation of sedimentation-rate history allowed by the strontium-isotope data (that is, abrupt changes in sedimentation rate at precisely the boundary level); however, sedimentological considerations, and measured strontium-isotope values at the boundary, support condensation rather than hiatus. Belemnite oxygen-isotope data suggest a significant temperature drop (~ 5 °C) across the boundary at this locality.

1. Introduction

A prime candidate for designation as the Global Stratotype Section and Point (GSSP) for the base of the Pliensbachian Stage is located at Robin Hood's Bay, Yorkshire, UK (Fig. 1). The boundary between Sinemurian and Pliensbachian strata occurs within the Redcar Mudstone Formation (Powell, 1984) and is particularly well exposed (Figs 2, 3) in wave-washed rock platforms and the cliff foot on the south side of the bay, at Wine Haven (a former harbour that served the adjacent Peak Alum Works). The Lias Group of Robin Hood's Bay has long been known for the richness of its ammonite faunas (Tate & Blake, 1876; Bairstow, 1969; Cope *et al*. 1980), although until recently the biostratigraphy has not been well documented. The Sinemurian–Pliensbachian boundary succession lies within the Pyritous Shales Member and comprises pale grey and buff-coloured sandy mudstones which pass upwards into silty dark grey shales (Sellwood, 1970; Hesselbo & Jenkyns, 1995). A review of European ammonite faunas (Dommergues & Meister, 1992) has indicated that this section exhibits the most complete ammonite faunal succession of the European region, thus spotlighting its potential for boundary definition. The purpose of the present paper is to detail the lithostratigraphy, ammonite biostratigraphy and isotope stratigraphy across the boundary, as a prelude to formal proposal of the section for GSSP status.

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2. Lithostratigraphy and depositional setting

The lithological succession as shown in Figure 4 resolves some of the differences existing between previously published sections for the locality, which had arisen from measurements being taken from both the foreshore (Dommergues & Meister, 1992) and cliff exposures (Hesselbo & Jenkyns, 1995). The upward transition from pale grey to dark grey shale is gradational. In the field, two of the most noticeable features of this interval are the 10 cm thick beds of concretionary siderite (Figs 2–4: Beds 70 and 72). Above the upper concretionary level, macrofossils are abundant and are concentrated into several discrete shell-beds. The whole succession was deposited in a shallow-marine environment, but the facies sequence from the upper part of the Sinemurian (Aplanatum Subzone) to the lower part of the Pliensbachian (Taylori Subzone) represents a long-term relative sea-level rise of at least regional extent, possibly global (Hallam,

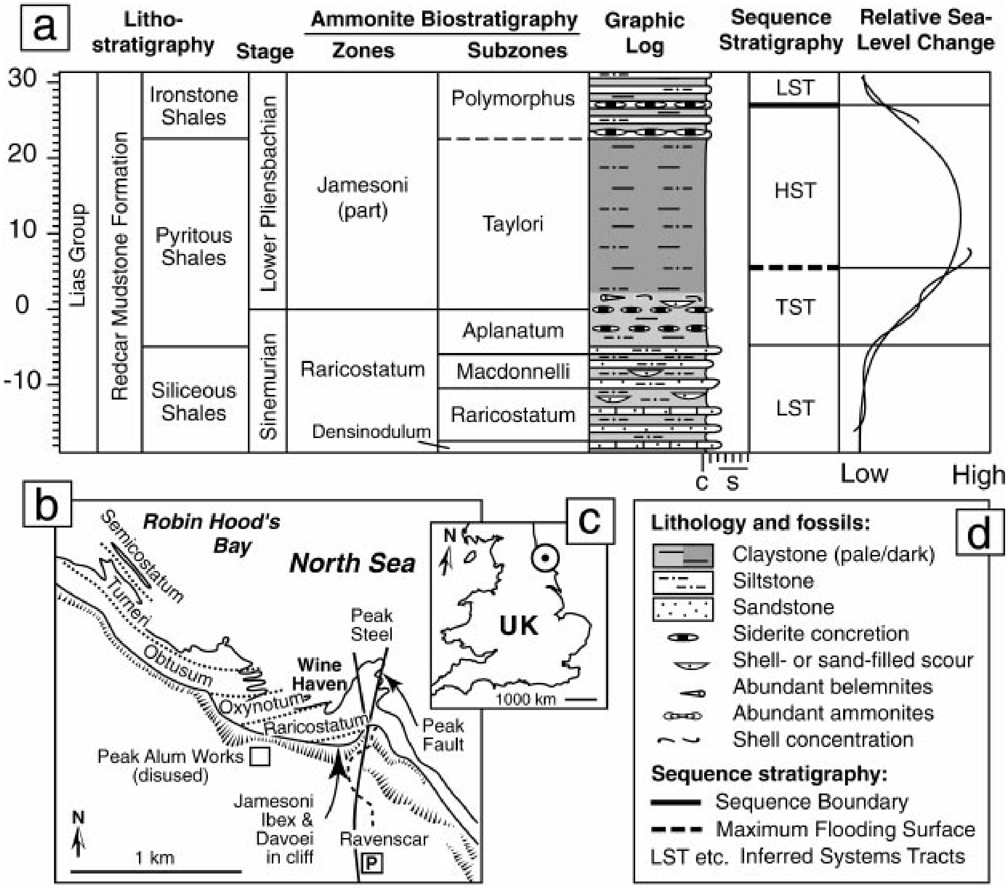

Figure 1. (a) Summary stratigraphic log for the Late Sinemurian to Early Pliensbachian succession of Robin Hood's Bay, Yorkshire, based on data in Hesselbo & Jenkyns (1995, 1998) and Cope *et al.* (1980). Vertical scale in metres. (b) Sketch geological map of the Wine Haven area showing distribution of strata in the inter-tidal zone (adapted from Rawson & Wright, 1992). (c) Location of Robin Hood's Bay. (d) Key to panel (a) and Figure 4. Sequence stratigraphic abbreviations: LST = Lowstand Systems Tract; TST = Transgressive Systems Tract; HST = Highstand Systems Tract.

1961, 1981; Sellwood, 1972; Hesselbo & Jenkyns, 1995, 1998; Van Buchem & Knox, 1998). The history of regional sea-level change is less clear for time-scales shorter than those of standard subzones; for example, the boundary beds on Skye, Hebrides Basin, are characterized by an apparently regressive unit that may be either of latest Sinemurian or earliest Pliensbachian age (Sellwood, 1972; Donovan, 1990; Morton & Hudson, 1995; Hesselbo, Oates & Jenkyns, 1998).

3. Ammonite biostratigraphy and biochronology

Following formal procedures (Callomon & Donovan, 1974; Salvador, 1994; Remane *et al.* 1996), the boundary between two stages must be founded on the unambiguous definition of the base of the upper stage. In the present case, the base of the Pliensbachian Stage is based on ammonite biostratigraphy and drawn at the bottom of the Taylori Subzone of the Jamesoni Zone (cf. Spath, 1923; Dean, Donovan & Howarth, 1961). The Taylori Subzone can be recognized widely across northwestern Europe, although beyond this region it can be identified only tentatively, based on eoderoceratid taxa that require further study.

The detailed ammonite succession has been determined across the Sinemurian–Pliensbachian boundary interval at Wine Haven (Dommergues & Meister, 1992). Work recently completed by us allows a precise placement of the boundary according to these ammonite faunas (Fig. 4). Of particular importance for correlation is a pyritized fauna including *Bifericeras donovani* Dommergues & Meister and juvenile *Apoderoceras* sp. which overlies the highest Upper Sinemurian echioceratid and underlies the lowest *Apoderoceras* gr. *aculeatum* (Simpson), characteristic of the Lower Pliensbachian. The different associations, grouped into horizons (cf. Callomon, 1995; Blau & Meister, 2000), are compatible with the standard biozonation of Dean, Donovan & Howarth (1961), and the standard succession of horizons proposed by Dommergues, Page & Meister (1994), Meister (1995), and Dommergues, Meister & Mouterde (1997). This biochronostratigraphic scheme is shown in Table 1.

After the disappearance of the Echioceratidae, a

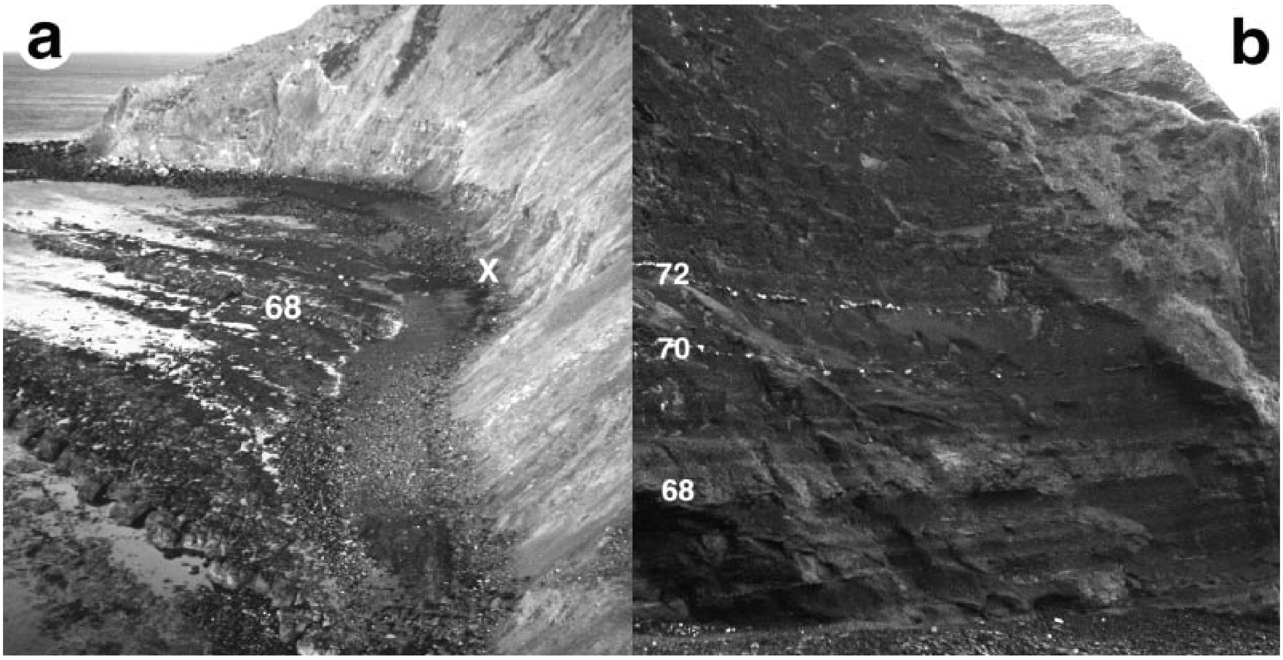

Figure 2. (a) View from a cliff-top ravine at Peak Alum Works (NZ 974 024) looking east towards Peak Steel (see Fig. 1). Bed 68 makes a step on the foreshore and is simply located. An easily accessible boundary section is usually available in wave-washed exposures at the foot of the cliff marked X. (b) The boundary beds exposed inaccessibly in the cliff below and east of the ravine from which photograph (a) was taken (NZ 975 024). The two main marker horizons are obvious here and can be traced down-dip into the cliff foot and foreshore exposure.

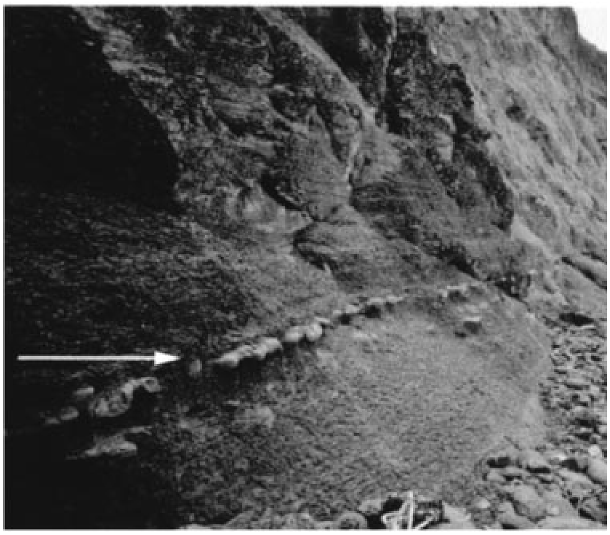

Figure 3. Detail of boundary at Wine Haven, Robin Hood's Bay (position X in Fig. 2a). Arrow indicates chosen position for boundary level. The prominent line of nodules forms Bed 72 (cf. Figs 2, 4).

Sinemurian family, the Eoderocerataceae superfamily split up (nomenclature *sensu* Donovan, Callomon & Howarth, 1981; Benton 1993). The species *Phricodoceras* gr. *taylori* (Sowerby) is mainly of Pliensbachian age, but is also known from rare specimens occurring with typically Late Sinemurian fossils (Dommergues & Meister, 1990). Thus, the position of the boundary is now based only on particular taxa of the Eoderocerataceae (*Apoderoceras nodogigas* (Quenstedt)–*leckenbyi* (Wright), *Apoderoceras* ssp., *Bifericeras donovani* Dommergues & Meister, *Tetraspidoceras quadrarmatum* (Dumortier)). Amongst this fauna, the presence of the genus *Apoderoceras* provides a useful indication for the first level of the Early Pliensbachian. Consequently, the boundary between the Pliensbachian and Sinemurian stages is placed very close to the base of Bed 73 (1011) in the Wine Haven section (6 cm above the mid-line of nodules forming Bed 72; Fig. 3). We note, however, that ammonites have not been recorded from the 1.8 m of strata below the proposed boundary level.

4. Isotope stratigraphy

4.a. Method

Belemnite samples were prepared using a method similar to that of Jones, Jenkyns & Hesselbo (1994). Strontium-isotope measurements were made using a modified VG 54E thermal ionization mass spectrometer. All $^{87}Sr/^{86}Sr$ values were internally normalized to $^{86}Sr/^{88}Sr$ ratio of 0.1194. During the period of analysis, the standard NBS987 gave an average $^{87}Sr/^{86}Sr$ value of 0.710248 (±0.000028 2σ, n = 5), Eimer & Amend was 0.708027 (±0.000018 2σ, n = 2), and USGS EN-1 was 0.709176 (±0.000030 2σ, n = 2). However, the long term (four year) average of the NBS987 standard from the Age & Isotope Laboratory, University of Oxford is 0.710256 (±0.000017 2σ, n = 242). All samples have

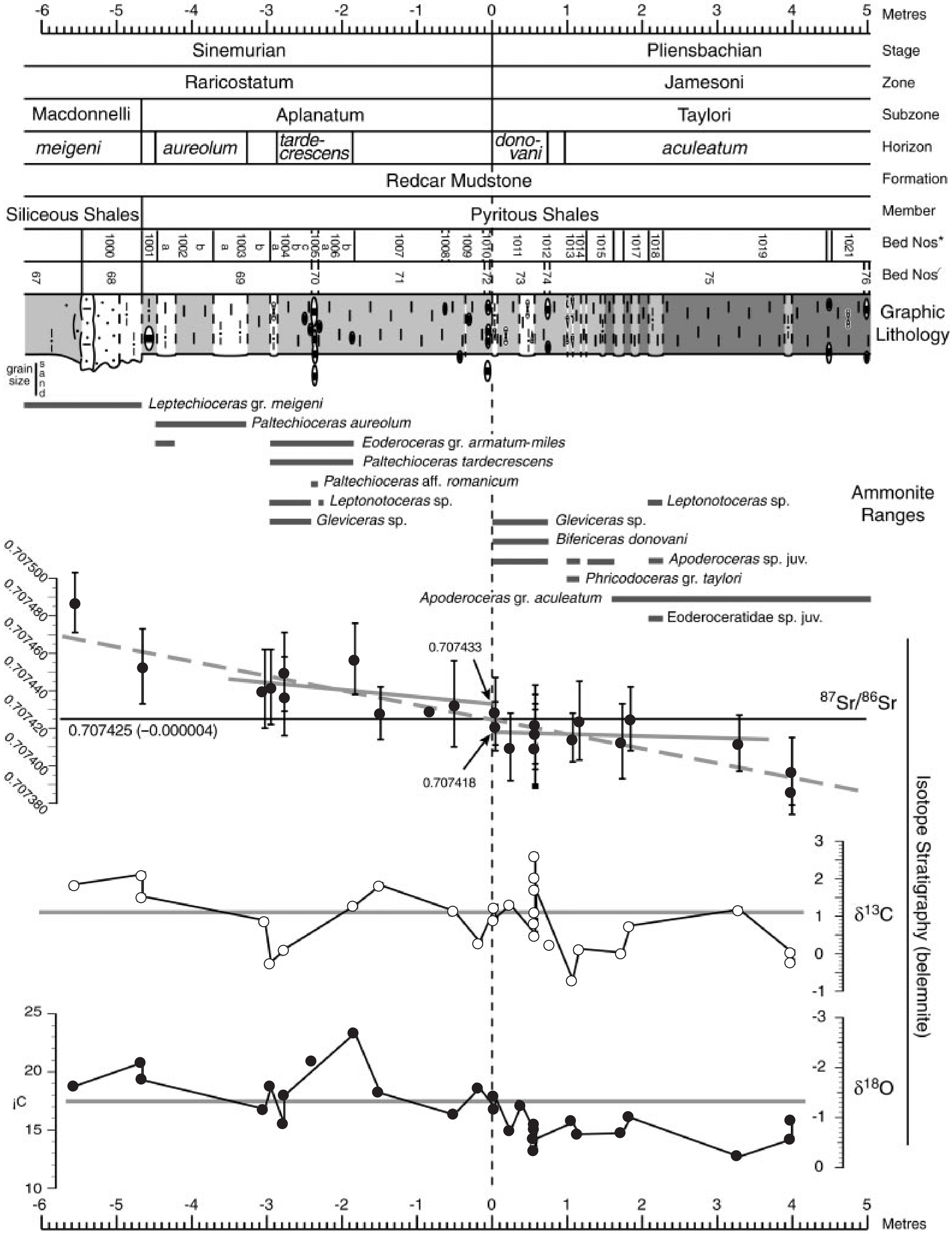

Figure 4. Detailed log of the Sinemurian–Pliensbachian boundary section at Wine Haven, Robin Hood's Bay. Bed numbers are from Dommergues & Meister (1992) (*) and Hesselbo & Jenkyns (1995) (§). Key as for Figure 1. Isotopic values are from diagenetically unaltered samples only. No ammonites have been recorded from between –1.8 m to 0 m in the section. Zones and Subzones are treated as biochronostratigraphic entities (that is, they have time significance). See text for further discussion.

Table 1. Scheme of zones, subzones and horizons at the Sinemurian–Pliensbachian boundary in Yorkshire.

Early Pliensbachian (Carixian, early part)
  Jamesoni Zone (early part)
    Taylori Subzone (early part)
      A. gr. *aculeatum* horizon: *Apoderoceras* gr. *aculeatum* (Simpson), *Apoderoceras* sp. juv., *Phricodoceras* gr. *taylori, Leptonotoceras* sp., Eoderoceratidae sp. juv.
      B. donovani horizon: *Bifericeras donovani* Dommergues & Meister, *Apoderoceras* sp. juv., *Gleviceras* sp.
Late Sinemurian (late part)
  Raricostatum Zone (late part)
    Aplanatum Subzone
      P. tardecrescens horizon: *Paltechioceras tardecrescens* (Hauer), *Paltechioceras* aff. *romanicum* (Uhlig), *Eoderoceras* gr. *armatum* (Sowerby) –*miles* (Simpson), *Leptonotoceras* sp., *Gleviceras* sp.
      P. aureolum horizon: *Paltechioceras aureolum* (Simpson), *Eoderoceras* gr. *armatum* (Sowerby) –*miles* (Simpson).
    Macdonnelli Subzone (late part)
      L. gr. *meigeini* horizon: *Leptechioceras* gr. *meigeni* (Hug).

Note: the *P. tardecrescens* horizon corresponds to the last known echioceratid in NW Europe and probably throughout the world.

been normalized to an assumed NBS987 value of 0.710250, by subtracting 0.000006 from all strontium-isotope results. Carbon and oxygen isotopes were analysed in a Prism mass spectrometer, and calibration to PDB was via a laboratory standard (Carrara Marble) calibrated to NBS 19.

4.b. Results and discussion

A detailed curve for the evolution of $^{87}Sr/^{86}Sr$ ratios in Jurassic seawater has been constructed using British Jurassic belemnites (Jones, Jenkyns & Hesselbo, 1994; Jones *et al.* 1994), including samples collected at Robin Hood's Bay. This work indicated that correlations based on strontium-isotope values would be of particular value for Early Jurassic time, and further suggested that stratigraphic breaks may be identified in successions by the presence of abrupt changes in strontium-isotope values across short stratigraphic intervals (Jones, Jenkyns & Hesselbo, 1994; cf. Miller, Liu & Feigenson, 1996; and description of data compilation in Howarth & McArthur, 1997).

The results of focused sampling for the present study are shown in Figure 4. Because of the strong possibility of incorporation of strontium from pore waters during diagenesis (Jones, Jenkyns & Hesselbo, 1994; Jones *et al.* 1994), all samples were prepared so as to avoid diagenetic calcite and analysed additionally for trace element contents. Any samples with >150 ppm Fe or >50 ppm Mn were deemed to be suspect and are not shown in the figure.

As expected from Jones, Jenkyns & Hesselbo (1994), $^{87}Sr/^{86}Sr$ ratios decrease upward through the sampled interval. A best-fit line through the whole dataset (square of difference of data points from line, divided by square of s.e. on individual analyses), gives a seawater $^{87}Sr/^{86}Sr$ ratio for the boundary level of 0.707425 with an uncertainty of ± 0.000004 (± 2 s.e).

Additional and alternative uncertainties associated with the new boundary value derive from two main sources. Firstly, the principal source of uncertainty is instrumental drift. Data cited in the method section indicate a long-term average value for the standard of 0.710256 (± 0.000017, 2σ, $n=242$). Secondly, although the lack of clear abrupt changes in strontium-isotope values through the section encourages the view that sedimentation was relatively continuous, the dataset does allow the *possibility* of condensation or minor hiatus at the boundary. Therefore, a lesser uncertainty relates to possible variations in sedimentation rate.

The most extreme effects of possible variations in sedimentation rate are illustrated by fitting straight lines through two subsets of the data: from four metres above the boundary, and from four metres below (Fig. 4). This is equivalent to a stratigraphic interpretation that the succession is made up of 4 m thick packages of rapidly deposited strata separated by a hiatus at the boundary itself. The result is an uncertainty in $^{87}Sr/^{86}Sr$ ratios of +0.000007 and –0.000008 which, by the most pessimistic view imaginable, translates into a hiatus lasting 360 k.y. (using the rate of change of strontium isotopes of –0.000042 per m.y. as calibrated against Early Pliensbachian Milankovitch cyclicity: Weedon & Jenkyns, 1999). However, the presence of shell beds in the vicinity of the boundary suggests minor condensation rather than hiatus; and this interpretation is supported by the average value of 0.707422 ± 0.000012 (± 2 s.e.) obtained from eight replicate analyses of two belemnites from 1 cm and 4 cm above the boundary level.

Correlation of another section to the Robin Hood's Bay stratotype could be achieved to a resolution approximately equivalent to an ammonite subzone on the basis of a similar dataset (the difference between $^{87}Sr/^{86}Sr$ ratios at the base and top of the Aplanatum Subzone is ~0.000035, and the change in ratios through the Taylori Subzone is somewhat greater).

Carbon-isotope values of belemnite calcite are highly variable through the sampled section, and if true stratigraphic patterns are reflected in the dataset, sample resolution is not sufficient to detect their presence unambiguously (Fig. 4). Belemnite oxygen isotopes, in contrast, show a stratigraphic trend towards less-negative values upwards across the boundary. Less-negative oxygen-isotope values signify lower temperatures in environmental settings where continental ice volume is invariant and evaporation or freshwater input are minor factors (e.g. Anderson & Arthur, 1983). Assuming that these conditions apply, palaeotemperatures decreased by ~5 °C, with the greatest changes taking place over ~0.5 m of strata above the boundary level. This palaeotemperature decrease could simply result from sampling belemnites whose habitat was in deeper (and thus cooler) water, but it may alternatively reflect more widespread palaeoceanographic changes occurring at the Sinemurian–Pliensbachian transition, such as a regional climatic cooling or a change in water-mass provenance.

5. Summary and conclusions

The coastal exposure at Wine Haven, Yorkshire, fulfils the principal criteria (Remane *et al*. 1996) for definition as GSSP for the base of the Pliensbachian Stage. The section is well exposed, relatively thick, lacks a major hiatus, and has not been subject to synsedimentary or tectonic disturbance; it contains an abundance of well-preserved marine fossils and does not show abrupt facies changes. The best candidate level for the boundary is at the base of the Taylori Subzone as characterized by the association of *Bifericeras donovani* and *Apoderoceras* sp. The seawater $^{87}Sr/^{86}Sr$ ratio at this level is 0.707425, with uncertainties of ±0.000017 (2σ) attached to measurement of the standard, and ±0.000004 associated with fitting a straight line through the whole stratigraphic dataset. Correlation to the boundary section based on either biostratigraphy or Sr-isotope stratigraphy should be of comparable global resolution, but there is considerable potential for improved correlation using either method. Belemnite oxygen-isotope data suggest a local seawater temperature drop of ~5 °C from the latest Sinemurian to the earliest Pliensbachian.

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