Isotopic and palynological evidence for a new Early Jurassic environmental perturbation

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a rticle info

Article history:
Received 1 June 2012
Received in revised form 18 September 2012
Accepted 17 October 2012
Available online 24 October 2012

Keywords:
Environmental change
Palynomorphs
Stable isotopes
Early Jurassic (Late Sinemurian)
Central England

a b s t r a c t

The Early Jurassic Epoch was a predominantly greenhouse phase of Earth history, but a comprehensive understanding of its climate dynamics is hampered by a lack of high resolution multi-proxy environmental records. Here we report a geologically brief (approximately several hundred thousand years) negative carbon isotope excursion (CIE) of 2–3‰ in both marine and terrestrial materials, recognised for the first time for the Late Sinemurian Substage (Early Jurassic, ~194 Ma) of eastern England. The Late Sinemurian carbon isotope excursion, which is termed the S-CIE herein, is accompanied by peaks in the abundance of the pollen grain Classopollis classoides and the dinoflagellate cyst Liasidium variabile. Classopollis classoides was thermophilic and is a reliable proxy for hot/warm climatic conditions. Liasidium variabile is interpreted as thermophilic and eutrophic using multivariate statistics, its fluorescence properties being similar to living heterotrophic dinoflagellate cysts, and its association with C. classoides. Moreover, the morphological and ecological similarities of L. variabile to the Cenozoic genus Apectodinium are noteworthy. The co-occurrence of the acmes of C. classoides and L. variabile with a negative CIE is interpreted here as having wide geographical significance due to the marine and terrestrial carbon isotope signals being precisely in phase within an open marine setting. This is consistent with an oceanic–atmospheric injection of isotopically-light carbon, coupled with global warming and increased marginal marine nutrient supply, possibly the result of increased precipitation due to an enhanced hydrological cycle or a seasonally-stratified water column. A probable sea level rise of at least regional extent has been identified at the L. variabile event in other records, which supports this putative phase of global warming. All these features are common to the Paleocene/Eocene thermal maximum (PETM, ~56 Ma), and there are also similarities with the Early Toarcian oceanic anoxic event (T-OAE, ~182 Ma).

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1. Introduction

The Jurassic Period was a mainly greenhouse phase of Earth history, characterised by global palaeotemperatures that were 5–10 °C higher than modern levels based on palaeo-modelling results (Chandler et al., 1992; Rees et al., 1999; Sellwood and Valdes, 2008). During the Early Jurassic the supercontinent Pangaea fragmented into Laurasia and Gondwana, creating major seaways including the proto Central Atlantic Ocean and marine connections between western Tethys and the north polar region (Fig. 1). Sea levels rose steadily throughout the Early Jurassic (Haq et al., 1987, 1988) and much of Europe and surrounding areas in the northern hemisphere were covered by warm, relatively shallow and stable epicontinental seas (summary in Coward et al., 2003). Sedimentation was dominated by rhythmic cycles of fossiliferous marine shelfal muds with subordinate carbonates and sands within large fault-bounded basins that were created by crustal extension. Northwest Europe probably lay around 10° south of its present latitude (Bradshaw et al., 1992). British Lower Jurassic stratigraphy has been summarised by Cope et al. (1980) and Simms et al. (2004). The Early Toarcian oceanic anoxic event (T-OAE, ~182 Ma according to the timescale of Gradstein et al., 2012) was a short-lived major phase of global warming during the late Early Jurassic, and is marked by a significant negative carbon isotope (δ13C) excursion (CIE) (Jenkyns, 2010). The T-OAE and other large CIEs have been interpreted as being due to the release of isotopically-light, largely biogenic methane from sub-seafloor accumulations of methane clathrate (Hesselbo et al., 2000; Kemp et al., 2005; Cohen et al., 2007). Similar, but smaller scale, events have also been recognised in the Early Jurassic at the Pliensbachian–Toarcian boundary (~183 Ma; Hesselbo et al., 2007; Bodin et al., 2010; Littler et al., 2010), and at the Sinemurian–Pliensbachian boundary (~191 Ma; Korte and Hesselbo, 2011).

In this study of a succession from eastern England, we report geochemical and palynological data which are consistent with another...
Early Jurassic warming event in the Late Sinemurian (~194 Ma). This evidence comprises a significant negative CIE (termed herein the S-CIE) which is temporally coincident with abundance acmes of the terrestrially-derived pollen grain *Classopollis classoides* and the marine dinoflagellate cyst *Liasidium variabile* (Figs. 2, 3). Both these taxa were thermophilic, and *L. variabile* has a narrow stratigraphical range.

The Mesozoic gymnosperm pollen *Classopollis* was produced by plants belonging to the family Cheirolepidiaceae. This genus is interpreted as being thermophilic and xerophytic and hence a proxy for hot/warm palaeotemperatures (e.g. Pocock and Jansonius, 1961; Srivastava, 1976). *Classopollis*-producing plants have been interpreted to have preferred both coastal and upland slope habitats (Batten, 1975; Filatoff, 1975).

The distinctive dinoflagellate cyst *L. variabile* is an index fossil for the Late Sinemurian of the northern hemisphere and is the oldest known peridinioid species (Brittain et al., 2010). In an interval characterised by extremely low dinoflagellate cyst diversities, *L. variabile* suddenly appeared, became abundant and abruptly disappeared. The range of *L. variabile* is typically entirely within the *Oxynoticeras oxynotum* ammonite Biozone, and this taxon has also been interpreted as a warm water species using multivariate statistics (Riding and Hubbard, 1999). Because of some similarities to the apparently thermophilic dinoflagellate cyst genus *Apectodinium* Costa and Downie, 1976, *L. variabile* has been suggested to have tracked warmer water polewards (Feist-Burkhardt, 2009).

These three linked phenomena are interpreted here as being consistent with a major biogeochemical perturbation associated with a brief phase of significant ocean/atmosphere carbon injection and global warming ~8 Ma prior to the T-OAE.

2. Material and methods

The Copper Hill Borehole was an exploratory stratigraphical borehole drilled by the British Geological Survey (BGS) during 1991 in Copper Hill Quarry, near Ancaster, Lincolnshire, eastern England; the national grid reference is SK 9787 4265 (Fig. 4; Berridge et al., 1999, fig. 19). The Lower and Middle Jurassic (Sinemurian to Bajocian) palynology of the Copper Hill Borehole was described by Riding (1992). The palynology samples were prepared using the standard acid digestion method including mild oxidation with cold nitric acid (Wood et al., 1996), and the rock samples, prepared organic residues, and microscope slides are all housed...
in the collections of the British Geological Survey, Keyworth, Nottingham NG12 5GG, United Kingdom.

For the carbon isotope analysis on the bulk and palynomorph concentrates, the samples were homogenised and treated with 5% hydrochloric acid to remove any calcite. $^{13}$C/$^{12}$C analyses were performed by combustion in a Costech Elemental Analyser (EA) on-line to a VG TripleTrap and Optima dual-inlet mass spectrometer, with $^{13}$C values calculated to the VPDB scale using within-run laboratory standards calibrated against NBS18, NBS-19 and NBS-22. Replicate analysis of well-mixed samples indicated a precision of $\pm 0.1\%$ (1 SD). For the belemnite carbon and oxygen isotope analysis, approximately 50 $\mu$g of carbonate was used for isotope analysis using a GV IsoPrime mass spectrometer plus Multiprep device. The isotope values ($\delta^{13}$C, $\delta^{18}$O) are reported as per mille ($\%$) deviations of the isotopic ratios ($^{13}$C/$^{12}$C, $^{18}$O/$^{16}$O) calculated to the VPDB scale using a within-run laboratory standard calibrated against NBS standards. Analytical reproducibility of the standard calcite (KCM) is $\pm 0.1\%$ for $\delta^{13}$C and $\delta^{18}$O.

The interval studied in the Copper Hill Borehole is relatively fossiliferous and the standard ammonite biozones and biosubzones have been determined (Tables 1–3). The ammonite biostratigraphy, however, is of limited utility in terms of identifying the duration of relatively short-lived palaeoclimatic events such as the S-CIE. The S-CIE is not currently well-constrained chronostratigraphically because there are no accurate estimates for the absolute age ranges of the three Late Sinemurian ammonite biozones as suitable cyclic sedimentary successions have not been studied. A cyclostratigraphical calibration of the long-term decline in seawater $^{87}$Sr/$^{86}$Sr values throughout the Early Jurassic gives an estimate for ammonite biozone duration of ~1 Ma each (Weedon and Jenkyns, 1999; Gradstein et al., 2012). This means that the S-CIE may have lasted a few hundred...
Table 1

| Depth (m) | Ammonite biozone | AQUATIC PALYNOMORPHS | POLLEN | SPORES | AQUATIC PALYNOMORPHS |
|----------|------------------|----------------------|--------|--------|----------------------|
| 150      | E. rari.          |                      | 1.5 X  | 1.7    | 10.5                 |
| 155      | E. rari.          |                      | X 2    | X      | 21.4                 |
| 160      | E. rari.          |                      | X 1    | X      | 21.4                 |
| 165      | E. rari.          |                      | X 1    | X      | 21.4                 |
| 170      | E. rari.          |                      | X 1    | X      | 21.4                 |
| 175      | E. rari.          |                      | X 1    | X      | 21.4                 |
| 180      | E. rari.          |                      | X 1    | X      | 21.4                 |
| 185      | E. rari.          |                      | X 1    | X      | 21.4                 |
| 190      | E. rari.          |                      | X 1    | X      | 21.4                 |
| 195      | E. rari.          |                      | X 1    | X      | 21.4                 |
| 200      | E. rari.          |                      | X 1    | X      | 21.4                 |

Note: X denotes the absence of the respective palynomorph. In the ammonite biozone/biosiszone column, the numbers in the cells are percentages. An X denotes that the respective palynomorph has been recorded outside the count. An ellipsis (…), denotes the absence of the respective palynomorph.
3. Palynomorph and kerogen assemblages

The palynofloras in 26 samples between 200 m and 150 m from the Sinemurian of the Copper Hill Borehole are illustrated in Table 1. The succession studied represents an open marine palaeoenvironment within a geographically extensive seaway (Coward et al., 2003). All the samples yielded abundant and well-preserved palynofloras of relatively low taxonomic diversity. The floras are overwhelmingly dominated by gymnospermous pollen grains, particularly bisaccate forms including Vitreisporites pallidus, Classopollis cladois and Perinopollenites elatoides. Classopollis cladois is a long-ranging species and is present throughout the entire Sinemurian to Bajocian succession drilled by the Copper Hill Borehole (Riding, 1992). The acme of this species is at 177 m, at which level it comprises 24.3% of the entire palynoflora and 32.5% of the terrestrial palynomorphs (Fig. 2; Tables 1, 2). This maximum is coincident with the lowest percentage (26.6%) of P. elatoides (Table 1). Other pollen present comprise Araucariacites australis, Cerebropollenites macrovulcosus and Chasmatospores spp. Pteridophyte spores are significantly subordinate to gymnospermous pollen, and are dominated by simple, smooth forms attributable to the genus Cyathidites. Other spores encountered include Baculatisporites/Osmundacidae spp., Concaussimsporites verrucosus, Coronatispora valdensis, Dictyophyllidites spp., Duplexisporites sp., Gleicheniophytes senonicus, Ischyosporites variagatus, Kraeuselisporites reissingeri, Neoarctrichia grishorpanos, Retitriletes austroclavatidites, Sestroporis pseudoaevolatus, Todisporites spp. and Uvaporites argenteaformis. Rare reworked Carboniferous spores were recognised; these include Densosporites spp., Lycospora pusilla and Tripartites vetustus. The freshwater/brackish alga Botryococcus is present in low proportions (Table 1).

Marine palynomorphs are present in consistently lower proportions than terrestrially-derived taxa. Liasidium variabile is the only dinoflagellate cyst recognised and was recorded between 182 m and 172 m, within the Upper Sinemurian part of the Brant Mudstone Formation, where it is largely confined to the O. oxynotum ammonite Biozone (Fig. 2; Tables 1–3). The acme of L. variabile is at 177 m, at which level it comprises 21.3% of the entire palynoflora (Fig. 2; Tables 1, 2). The marine acanthomorph acritarch genus Micryhystridium is present throughout in significant proportions. Other marine palynomorphs are present in low numbers; these are foraminiferal test linings, Tasmanites spp. and Veryhachium sp. (Table 1). The palynomorph species recognised in this study are listed, with author citations, in Appendix 1. The palynology of the entire Lower and thousand years, which is comparable to the Paleocene/Eocene thermal maximum (PETM. – 56 Ma). Other potentially analogous CIEs are at the T-OAE, which has a poorly constrained duration of ~200–900 ka (Suan et al., 2008; Kemp et al., 2011), and at the Selli Event in the Early Aptian (~120 Ma). The Selli Event, or OAE 1a, was reported to have lasted 1.11 ± 0.11 Ma by Malinverno et al. (2010).

Table 2

| Substage       | Ammonite biozones | Depth (m) | Bulk organic C | Belemnites | Paly. conc. | L. variabile | C. classoides |
|----------------|-------------------|-----------|----------------|------------|-------------|--------------|---------------|
|                |                   |           | $\delta ^{13}$Corg | $\delta ^{13}$Cpel | $\delta ^{13}$Opel | (%)          | (%)           |
| Upper Sinemurian | E.rar./Lm         | 150       | −25.3          | +2.00      | −1.13       | ...           | 2.9            |
|                 |                   | 153       | −25.2          | +2.00      | −1.13       | ...           | 5.4            |
|                 |                   | 155       | −25.2          | +2.00      | −1.13       | ...           | 9.5            |
|                 |                   | 158       | −24.8          | −24.8      | ...         | ...           | 7.6            |
|                 |                   | 160       | −24.5          | −24.8      | ...         | ...           | 10.5           |
|                 |                   | 163       | −24.5          | −24.8      | ...         | ...           | 15.5           |
|                 |                   | 165       | −23.9          | −24.3      | ...         | ...           | 15.5           |
|                 |                   | 166       | −23.9          | −24.3      | ...         | ...           | 15.5           |
|                 |                   | 167       | −23.6          | −24.3      | ...         | ...           | 15.5           |
|                 |                   | 168       | −24.4          | +3.42      | −1.81       | ...           | 15.5           |
|                 |                   | 169       | −24.7          | +3.42      | −1.81       | ...           | 15.5           |
|                 |                   | 170       | −24.4          | +3.42      | −1.81       | ...           | 15.5           |
|                 |                   | 171       | −24.2          | −24.3      | ...         | ...           | 15.5           |
|                 |                   | 172       | −24.5          | −24.3      | ...         | ...           | 15.5           |
|                 |                   | 173       | −24.6          | −24.3      | ...         | ...           | 15.5           |
|                 |                   | 174       | −24.5          | −24.3      | ...         | ...           | 15.5           |
|                 |                   | 175       | −25.1          | −24.3      | ...         | ...           | 15.5           |
|                 |                   | 176       | −25.7          | −24.3      | ...         | ...           | 15.5           |
|                 |                   | 177       | −25.8          | −24.3      | ...         | ...           | 15.5           |
|                 |                   | 178       | −25.6          | +1.24      | −1.50       | 7.3           | 23             |
|                 |                   | 179       | −26.0          | +1.24      | −1.50       | 4.3           | 16.2           |
|                 |                   | 180       | −25.9          | +1.24      | −1.50       | 9.9           | 13.1           |
|                 |                   | 181       | −25.8          | +1.24      | −1.50       | 3.4           | 14.5           |
|                 |                   | 182       | −25.1          | +1.24      | −1.50       | 3.6           | 19.2           |
|                 |                   | 183       | −24.6          | +2.05      | −1.75       | ...           | 5.4            |
|                 |                   | 184       | −24.9          | +2.05      | −1.75       | ...           | 5.4            |
|                 |                   | 185       | −25.1          | +2.05      | −1.75       | ...           | 5.4            |
|                 |                   | 186       | −25.6          | +2.05      | −1.75       | ...           | 5.4            |
|                 |                   | 187       | −25.0          | +2.05      | −1.75       | ...           | 5.4            |
|                 |                   | 189       | −24.5          | +2.05      | −1.75       | ...           | 5.4            |
|                 |                   | 191       | −23.6          | +2.05      | −1.75       | ...           | 5.4            |
|                 |                   | 192       | −23.6          | +2.05      | −1.75       | ...           | 5.4            |
|                 |                   | 194       | −23.4          | +2.05      | −1.75       | ...           | 5.4            |
|                 |                   | 196       | −23.8          | +2.05      | −1.75       | ...           | 5.4            |
|                 |                   | 198       | −24.1          | +3.24      | −1.89       | ...           | 6.5            |
|                 |                   | 200       | −23.8          | +3.24      | −1.89       | ...           | 6.5            |
|                 |                   | 201       | −24.0          | +3.24      | −1.89       | ...           | 6.5            |
Middle Jurassic (Sinemurian–Bajocian) succession cored by the Copper Hill Borehole was documented by Riding (1992).

The percentages of the main kerogen macerals are given in Table 3. The organic residues are generally dominated by palynomorphs. Black wood and various plant tissues are subordinate to palynomorphs. Amorphous organic material (AOM) is largely relatively rare, although it is most abundant at 179 m where it attained 32% (Table 3).

### Table 3

| Stratigraphy       | Depth (m) | Percentages of the principal kerogen macerals | Palynomorphs | % terrestrial | % marine |
|--------------------|-----------|-----------------------------------------------|--------------|--------------|----------|
| Upper Sinemurian   | 150       | 18                                             | 15           | 57           | 95.2     | 4.8      |
|                    | 155       | 8                                              | 17           | 70           | 96       | 4        |
|                    | 160       | 18                                             | 18           | 60           | 94.6     | 5.4      |
|                    | 165       | 12                                             | 12           | 70           | 94.7     | 5.3      |
|                    | 167       | 18                                             | 15           | 55           | 96.1     | 3.9      |
|                    | 169       | 22                                             | 12           | 60           | 95.6     | 4.4      |
|                    | 171       | 20                                             | 8            | 67           | 93.3     | 6.7      |
|                    | 172       | 17                                             | 12           | 68           | 88       | 12       |
|                    | 173       | 8                                              | 12           | 77           | 83.5     | 16.5     |
|                    | 174       | 12                                             | 16           | 70           | 80.9     | 19.1     |
|                    | 175       | 12                                             | 8             | 73           | 84.6     | 15.4     |
|                    | 176       | 12                                             | 12           | 70           | 76.3     | 23.7     |
|                    | 177       | 12                                             | 15           | 68           | 74.8     | 25.2     |
|                    | 178       | 8                                              | 7             | 75           | 86       | 14       |
|                    | 179       | 15                                             | 10           | 43           | 90.7     | 9.3      |
|                    | 180       | 10                                             | 12           | 63           | 81.4     | 18.6     |
|                    | 181       | 18                                             | 14           | 50           | 91.6     | 8.4      |
|                    | 182       | 15                                             | 12           | 65           | 91.8     | 8.2      |
|                    | 183       | 17                                             | 15           | 47           | 89.2     | 10.8     |
|                    | 185       | 15                                             | 13           | 64           | 76.3     | 23.7     |
|                    | 187       | 12                                             | 13           | 70           | 82.6     | 17.4     |
|                    | 189       | 23                                             | 18           | 44           | 84.1     | 15.9     |
|                    | 191       | 22                                             | 25           | 42           | 91.5     | 8.5      |
|                    | 192       | 25                                             | 30           | 53           | 91.4     | 8.6      |
|                    | 198       | 18                                             | 25           | 40           | 91.5     | 8.5      |
|                    | 200       | 23                                             | 32           | 37           | 92.1     | 7.9      |

In contrast to the carbon isotope record, the δ18Obelemnite values are relatively uniform (Fig. 2; Table 2) (mean δ18O = −1.6 ± 0.3‰). Although the negative CIE and the coincident Classopollis classoides and L. variabile peaks are inferred here to represent a period of global warming, the lack of a clear warming signal from belemnites may represent the effect of sea level rise due to thermal expansion of seawater, and hence locally deeper cooler water, as has recently also been suggested for the Sinemurian–Plenusianian boundary (Korte and Hesselbo, 2011). Alternatively, water column stratification and/or local upwelling of cool intermediate waters may have increased. It is not possible to use TEX86 or MBT/CBT as temperature proxies because the succession studied here is too thermally mature. Indeed, most Triassic and Jurassic successions have been too thermally altered for these methods, which have been used successfully on Early Cretaceous to modern material (Kuyper et al., 2001; Schouten et al., 2002).

### 4. Carbon and oxygen isotope geochemistry

Carbon isotope values were obtained from bulk organic matter, palynomorph concentrates and belemnite fragments between 201 m and 150 m in the Copper Hill Borehole; these geochemical data are given in Table 2. This interval includes the acme of Classopollis classoides and is within and adjacent to the range of L. variabile (Table 2). The materials analysed are both terrestrial and marine and thus allow a test as to whether any carbon isotope perturbation affected the global carbon cycle. Specifically, the palynomorph concentrates are dominated by terrestrial materials and the belemnite fragments represent the marine realm. A consistent negative CIE of 2–3‰ occurs in the Copper Hill Borehole (Fig. 2). The CIE as defined by the bulk sample δ13Corg is broadly symmetrical, and is recorded between 187 m and 176 m. There are two separate peaks; an older one at 186 m and a younger, larger one at 179 m (Fig. 2). The negative CIE is also recorded in the δ13C of palynomorph concentrates, which are overwhelmingly dominated by terrestrial material such as wood fragments, pollen and spores, and hence in part reflect isotopic changes in atmospheric CO2 in addition to a potentially minor unknown contribution from changing vegetation types. The δ13C values of the only five belemnites (nekto-benthic marine molluscs) recovered in this interval also show a negative CIE. The peak excursion of all three materials is temporally coincident with the acme of Classopollis classoides and L. variabile (Fig. 2).
and cooler palaeolatitudes (Vakhrameev, 1981). A similar distribution pattern was observed in North America by Pocock (1972).

There has been considerable debate as to the precise palaeoecological preference of Classopollis–producing plants. The genus has been reported in high proportions from near-coastal settings such as sandy bars or coastal islands with well-drained soils (Batten, 1975; Srivastava, 1976; Alvin, 1982; Abbink, 1998). This distribution led Batten and Maclennan (1984) to propose that the family Cheirolepidiaceae were possibly salt marsh shrubs or trees resembling modern mangroves. However Filatoff (1975, fig. 10) and Vakhrameev and Doludenko (1977) suggested that the Cheirolepidiaceae preferred upland slope habitats, and that the abundant Classopollis pollen preserved in nearshore palaeoenvironments was therefore allochthonous. Furthermore, several authors, such as Vakhrameev (1970), considered the Cheirolepidiaceae to be drought-resistant, thermophilous, xerophytic shrubs and trees which resembled modern juniper bushes.

The occurrence of abundant Classopollis during a global warming event is somewhat inconsistent with this genus being a proxy for dry (semi-arid to arid) conditions as suggested by, for example, Pocock and Jansonius (1961), Pocock (1972 and Vakhrameev 1991). This is because global warming events are normally associated with an enhanced hydrological cycle, and Classopollis has an extremely wide geographical distribution. Hence the conclusions of Batten and Maclennan (1984) that the parent plants of Classopollis were salt marsh or mangrove shrubs/trees are supported herein. However, it is possible that the Cheirolepidiaceae lived in a wide variety of habitats and that they could also survive in semi-arid to arid conditions.

5.2. Other pollen and spores

The remaining pollen and spore floras are typical of Sinemurian terrestrial palynoflora from Europe (e.g. Srivastava, 1987). The non-Classopollis gymnosperm pollen is dominated by coniferous plants from the orders Pinales and Cycadales. For example Peripolles nitidae elatae belongs to the Family Cupressaceae (cypresses). These groups are generally widely distributed, and hence are not especially palaeoecologically significant. However, Chasmatosporites is a possible representative of the Order Cycadales (see Pocock and Jansonius, 1969), and these forms are typical of subtropical and tropical regions today. The majority of the spores are from ferns or club mosses. These groups have extensive geographical extents today. However, Ischyosporites variegatus belongs to the chiefly tropical Family Schizeaceae (see Couper, 1958). Therefore, the other pollen and spores support the warm climate signal provided by Classopollis classoides, and are entirely consistent with an equable, subtropical setting.

5.3. The dinoflagellate cyst L. variabile

The dinoflagellate cyst L. variabile was originally described from the Upper Sinemurian strata of southwest Germany by Drugg (1978). Despite relatively little being known concerning the tabulation style of this species, the accepted view is that L. variabile is the oldest known representative of the order Peridiniales (Bujak and Davies, 1983, p. 56; Evitt, 1985, p. 176, 177; Fensome et al., 1993, p. 121). Its morphology was thoroughly reviewed by Below (1987, p. 128), who noted that the tabulation of this species is not fully developed and that the size and shape of the archaeopyle differ from most other peridiniane taxa in being unusually large. Furthermore the anterior margin of the archaeopyle is geniculate and it lies near to the apex, encroaching on the apical horn (Below, 1987, fig. 68). Riding and Hubbard (1999, p. 27) interpreted L. variabile as a warm water species based on evidence derived from the study of a comprehensive database of Jurassic dinoflagellate cysts using principal component analysis.

Liatidium variabile is an excellent marker for the Upper Sinemurian of the northern hemisphere (Riding, 1987; Poulsen and Riding, 2003; van de Schootbrugge et al., 2005; Brittain et al., 2010). This species is especially prominent in, and characteristic of, the O. oxynotum ammonite Biozone (~192–191 Ma) of northwest Europe, and is confined to northwest Europe and offshore eastern Canada (Williams et al., 1990) and has not been reliably reported elsewhere (Fig. 1). Dinoflagellates have a planktonic habit, some taxa also having a benthic resting cyst phase (Taylor, 1987). Thus the apparent geographical restriction of L. variabile to northwest Europe and offshore eastern Canada is deemed to reflect the lack of suitable studies of the Lower Jurassic from Africa, the Middle East, South America and southern Asia, coupled with the dominance of non-marine facies in the Early Jurassic of regions such as, for example, Russia and Australia (Riding et al., 1999, 2010).

Lower Jurassic dinoflagellate cyst assemblages have low species richness, especially in the Hettangian to Lower Pliensbachian (Bujak and Williams, 1979; Woollam and Riding, 1983; Fensome et al., 1996, 1999; MacRae et al., 1996). Upper Sinemurian successions yielding L. variabile are frequently underlain and overlain by strata that are entirely devoid of other dinoflagellate cysts (e.g. Riding, 1987, fig. 3). Van de Schootbrugge et al. (2005, p. 87–88) discussed the highly unusual sudden appearance, abundance and disappearance of L. variabile in Europe and eastern Canada, and explained this stratigraphically isolated acme as being due to major palaeoceanographical change, possibly linked to the opening and flooding of the Hispanic Corridor. These authors suggested that L. variabile migrated into Europe and eastern Canada from western Panthalassa through the Hispanic Corridor into the western Tethys in response to changes in ocean circulation during a sea-level highstand. This contention, however, is somewhat speculative because there are no records of L. variabile from Central America and the eastern Pacific area (Brittain et al., 2010, p. 72). It is equally possible, however, that L. variabile migrated northwards into Europe from western Tethys. This putative northerly migration of L. variabile may be an indication that this species tracked warmer water northwards. This contention is consistent with the interpretation of L. variabile as a thermophilic species by Riding and Hubbard (1999), and certain similarities between L. variabile and the peridinioid genus Apectodinium.

Feist-Burkhardt (2009) suggested that the acme of L. variabile in the Late Sinemurian is similar to the abundant occurrence of Apectodinium at the PETM, and also demonstrated that some specimens of L. variabile in unoxidised material exhibit dark brown-pigmentation with low autofluorescence intensities (Fig. 5). No pigmented forms were found in the Copper Hill Borehole material, but these samples were all oxidised using nitric acid during the preparation procedure which may have had a bleaching effect. Extant pigmented dinoflagellate cysts, such as produced by Archaeperidinium, Congruentidium and Protoperidinium, with little or no autofluorescence are all heterotrophic (Head, 1994, 1996; Brenner and Biebow, 2001). These characteristics led Feist-Burkhardt (2009) to conclude that L. variabile may have been produced by a heterotrophic and thermophilic dinoflagellate by analogy with extant floras, supposedly like the (consistently non-pigmented) genus Apectodinium. However, the peridinioid affinity of L. variabile is not prima facie evidence of this species being indicative of elevated sea surface temperatures; as with Apectodinium, palaeotemperature is one of several parameters which controlled its distribution.

There are, however, possible alternatives to L. variabile being a warm-water species. For example, a rise in sea level may have caused salinity changes that led to the influx of L. variabile during the Late Sinemurian. Alternatively, upwelling cold oceanic waters may have introduced an influx of nutrients which caused the acme of L. variabile at this time. The low-resolution but apparently invariant levels of δ18O throughout the succession studied (Fig. 2; Korte and Hesselsbo, 2011) would be consistent with this hypothesis. Despite these caveats, multivariate statistical evidence based on principal component analysis of the thermophilic nature of this species developed by Riding and Hubbard (1999), together with the co-occurrence of
5.4. The dinoflagellate cyst genus Apectodinium

The comparison of *L. variabile* to the Paleogene genus *Apectodinium* by Feist-Burkhardt (2009) mentioned above in Section 5.3 is an important one in the context of this contribution. Both these peridinian taxa have relatively transient acmes, and *Apectodinium* has been considered to be both heterotrophic and thermophilic (e.g. Crouch et al., 2003b). It should however be emphasised that, other than a shared peridinian affinity and therefore a probable heterotrophic feeding strategy, similarities between these taxa are relatively few. This is especially the case in terms of morphology. *Apectodinium* has a subpentagonal outline, exhibits a quadra-style archaeopyle, typically bears five horns, is cornucavate and is consistently unpigmented (Costa and Downie, 1976, 1979; Harland, 1979). By contrast, *L. variabile* is biconical, normally with two horns, acavate, has a large, heptagonal anterior intercalary (type I) archaeopyle and is occasionally pigmented (Drugg, 1978; Bucefalo Palliani and Riding, 2000, Figs. 5, 6; Feist-Burkhardt, 2009). The similarities between *L. variabile* and *Apectodinium* are mostly autoecological, i.e. are related to their similar geological settings. Both these taxa probably exploited rising sea levels and warming climates that would have caused the widespread development of water-column stratification on the continental shelves. These conditions may have caused algal blooms, thereby providing a food source for the heterotrophic motile dinoflagellate stages.

The palaeoecological preference of *Apectodinium* has recently been extensively debated. It is known as a neritic genus that thrived in estuarine settings (Crouch et al., 2003a; Slujs et al., 2005). At low-mid latitudes, *Apectodinium* typically comprises >40% of the dinoflagellate cyst associations during the PETM (e.g. Crouch et al., 2003b; Slujs et al., 2007; Kender et al., 2012). By contrast, *Apectodinium* is less common (~20%) in the Arctic, where low salinity dinoflagellate cysts increase (Slujs et al., 2006; Harding et al., 2011). Several studies have concluded that, due to the low latitude preference of *Apectodinium*, it must have tracked warm water northwards during the PETM (e.g. Crouch et al., 2003a). However, Canonical Correspondence Analysis (CCA) data from the New Jersey Shelf indicates that *Apectodinium* has only a weak correlation with palaeotemperature based on TEX86 (Slujs and Brinkhuis, 2009, p. 1791). Furthermore, Slujs et al. (2009) found that *Apectodinium* is generally absent throughout another hyperthermal event, the Eocene thermal maximum 2 (ETM2). Recently, Slujs et al. (2011, fig. 4) reported the main peak in abundance of *Apectodinium* occurred well before the PETM at ODP Site 1172 on the East Tasman Plateau. The principal acme of *Apectodinium* at this locality attained >60% of the assemblage at ~0.8 m below the thermal peak of the PETM. Following a decrease to around 2% there was a later peak of *Apectodinium*, attaining ~30% of the assemblage, within the PETM (Slujs et al., 2011, fig. 3). The fact that the older, more significant, acme of *Apectodinium* on the East Tasman Plateau is associated with normal sea surface temperatures (~26 °C) clearly indicates that this genus responded to variables other than simply temperature. For example, abundant *Apectodinium* has been interpreted as being indicative of elevated nutrient levels, water stratification and low salinities by Crouch et al. (2003b), Slujs et al. (2008) and Kender et al. (2012). This is also consistent with a warming world and elevated fluvial nutrient runoff from an associated enhanced hydrological cycle with greater precipitation in mid-high latitudes (Pagani et al., 2006). In conclusion, *Apectodinium* is normally abundant during the PETM, but temperature is only one of several factors which controlled its abundance.

Several authors have stated that the genus *Apectodinium* was probably heterotrophic and fed on other plankton and/or organic detritus (e.g. Brinkhuis et al., 1992, 1994; Crouch et al., 2003b; Slujs et al., 2005). This interpretation of trophic mode is based on the morphological similarity of *Apectodinium* with modern cysts of the unequivocally heterotrophic genus *Protoperidinium* (subfamily *Protoperidinioideae*). The vast majority of living protoperidiniacean dinoflagellates (including the diplapsalioideans) produces pigmented cysts, thus indicating that pigmentation is connected to heterotrophy in this group of dinoflagellates (Head, 1994, 1996; Rochon et al., 1999; Brenner and Biebow, 2001). However, *Apectodinium* belongs to the subfamily Wetzelielloideae (see Fensome et al., 1993). *Apectodinium* and cysts of *Protoperidinium* are hence both members of the suborder Peridinioideae, but there are substantial familial and subfamilial differences which are based on significant differences in tabulation style. The subfamily Wetzelielloideae has, for example, a quadra-style 2a plate, a stable epicystal tabulation and a fully subdivided cingulum. In contrast, cysts of the subfamily Protoperidinioideae are characterised by a highly variable cinctoid or bipesiid epicystal tabulation and a largely undivided cingulum (Fensome et al., 1993). The subpentagonal outline of *Apectodinium* is not a primary characteristic of the subfamily *Protoperidinioideae* (see Fensome et al., 1993, fig. 142). Hence, the evidence for heterotrophy in *Apectodinium*, based on similarities to cysts of *Protoperidinium* at the suborder level, appears to be purely circumstantial.

Several studies from marginal marine environments suggest an elevation in levels of marine nutrients in shelf seas, possibly in response to an intensification of increased weathering, terrestrial runoff and/or water column stratification during the PETM (e.g. Crouch et al., 2003b; Slujs et al., 2006, 2007; Slujs and Brinkhuis, 2009; Harding et al., 2011; Kender et al., 2012). It is highly likely therefore that the abundance of *Apectodinium* at or around the PETM is an indirect response to higher global palaeotemperatures and/or eutrophication.

6. Similarities of the S-CIE to other environmental change events

The temporal coincidence of the highly restricted thermophilic/neritic *L. variabile* and the thermophilic *Classopollis* acmes in the
Copper Hill Borehole, with a marked negative CIE (Fig. 2), suggests that the inferred environmental changes were associated with a perturbation to the carbon cycle. This may have been global in nature due to isotope excursions in both marine and terrestrial materials. Furthermore, the palynological records appear to be at least regional in extent. Van de Schootbrugge et al. (2005, table 3) also recorded coincident abundances of *Claspolis* spp. and *L. variabile* in the Late Sinemurian strata of the Mochras Borehole, northwest Wales. Our new records are similar in some respects to other Mesozoic and Cenozoic hyperthermal events such as the T-OAE and the PETM (Cohen et al., 2007), which exhibit negative CIEs coeval with global warming and major changes in marine palynomorph assemblages. Furthermore, the S-CIE association with the peridininacean dinoflagellate cyst *L. variabile* exhibits a striking similarity to the PETM. The latter hyperthermal event, occurring ~56 Ma ago, is characterised by a negative CIE and abundant levels of the peridininacean genus *Apectodinium* (e.g. Crouch et al., 2003b). During the PETM, the proportion of isotopically-light carbon in the atmosphere and oceans rapidly increased, hypothetically due to the catastrophic destabilisation of methane clathrate, magmatic heating of organic-rich sediments or direct volcanic outgassing (e.g. Dickens, 2011). The PETM is a particularly well-documented hyperthermal event ~56 Ma ago, that lasted approximately 120–220 ka (Röhl et al., 2007; Murphy et al., 2010). The duration of the S-CIE may have been a few hundred thousand years, which is therefore comparable to the PETM and the T-OAE (see above, Section 2).

The negative CIEs at the T-OAE, OAE 1a and the PETM are similar in form to that of the S-CIE (Fig. 6; Gröcke et al., 1999; Mort et al., 2007; Kuhnt et al., 2011). The 2–3‰ magnitude of the S-CIE is also similar to that of carbonate records of OAE 1a (e.g. Mort et al., 2007; Jenkyns, 2010). However, the magnitude of the S-CIE is smaller than that of the organic PETM (~5‰; summary in McInerney and Wing, 2011) and many T-OAE records (6‰; e.g. Hesselbo et al., 2007; Hermoso et al., 2009), suggesting either a smaller volume of injected carbon and/or a heavier isotopic value. The pulsed onset of the S-CIE is similar to those of the T-OAE, OAE 1a, and PETM (Fig. 6). However the S-CIE is of a much longer duration (~1 Ma) at the Early–Late Sinemurian transition in the Copper Hill Borehole, being perhaps therefore closer in character to the excursion at the Pliensbachian–Toarcian boundary followed by the T-OAE (Hesselbo et al., 2007). Specifically, the δ¹³C (bulk) record of the S-CIE shows an initial isolated spike at 186 m in the upper *Coenites turneri* and *Asteroceras obtusum* ammonite biozones, followed by a partial δ¹³C recovery towards pre-S-CIE levels, before the main part of the S-CIE at 179 m (Fig. 2). It is possible that the initial onset of the S-CIE at 190 m represents an early phase of warming that was temporarily reversed, either by a reduction in carbon injection and/or by negative feedbacks. It is noteworthy that the range base of *L. variabile* and the onset of the *Claspolis classoides* acme are coincident with the largest (second) negative pulse at ~180 m (Fig. 2), which we therefore infer to represent the largest environmental shift. In the Copper Hill Borehole, the onset of this main phase of the S-CIE coincides with the Glebe Farm Bed, an erosional horizon containing a concentration of bored carbonate nodules (Fig. 2; Brandon et al., 1990) that also represents the base of the *O. oxynotum* ammonite Biozone. Thus the record reported here is interrupted by a hiatus and is unlikely to represent the full extent of this palaeoenvironmental perturbation.

The aforementioned Toarcian, Aptian and Paleogene CIE events have been hypothesised to be due to injections of isotopically-light carbon into the ocean–atmosphere system (e.g. Dickens et al., 1997; Hesselbo et al., 2000), and this is likely also to be the case for the S-CIE. Another possible cause of a negative carbon excursion could be a contracting biosphere due to cooling, but this would be evident as major changes in biomes and very extensive glaciation for which there is no evidence at this particular time (Sellwood and Valdes, 2008; Korte and Hesselbo, 2011). The coincident and transient nature of the range and acme of *L. variabile*, the acme of *Claspolis classoides* and the S-CIE is high suggestive of a global warming event associated with carbon injection event.

There is as yet no known major magmatic/volcanic event, or previously reported indication of significant global warmth, during the Late Sinemurian. Furthermore, there are no known planktonic and/or vegetational changes in the Late Sinemurian that could have significantly affected the bulk carbon isotope signal. However, there is some evidence for a sea-level rise of at least regional scale over this interval (Hq et al., 1988), which is consistent with a period of global warmth. The upper part of the *A. obtusum* and the lower part of the *O. oxynotum* ammonite biozones represent an interval of shale
deposition associated with relative sea-level rise in the Cleveland Basin, northern England (Hesselbo and Jenkyns, 1998; Van Buchem and Knox, 1998). Similarly, the lithology of Late Sinemurian age strata on Skye, in the Hebrides Basin, northwest Scotland, closely approaches black (i.e., organic-rich) shale in the O. oxynotum ammonite Biozone (Hesselbo et al., 1998) and Brittain et al. (2010) reported L. variabile from coeval strata on Raasay in the Inner Hebrides. As well as indicating relative sea-level rise in this example, organic-rich shale is typical of deposition in stratified marine waters during periods of global warming and high nutrient levels such as the T-OAE, OAE 1a and PETM. The Late Sinemurian is represented by hiatus concretions and an omission surface on the Dorset coast in the Wessex Basin, southern England (Coe and Hesselbo, 2000), interpreted by Haq et al. (1988) and Hesselbo and Palmer (1992) to have resulted from bioerosion during a period of regional sediment starvation caused by sea-level rise (contra Hallam, 1999). The Glebe Farm Bed in the Copper Hill Borehole (Fig. 2), overlain by mudstone, grading upwards to sandstone, probably represents the same condensation phenomenon brought about by sea-level rise and deepening (upper A. obtusum and lower O. oxynotum ammonite biozones), followed by progradation and shallowing (upper O. oxynotum ammonite Biozone) (Hesselbo, 2008).

7. Conclusions

This study demonstrates that a significant abundance of the thermophilic pollen Classopollis classoides and the range and acme of the thermophilic/eutrophic dinoflagellate cyst L. variabile are linked with a marked coincident negative CIE (herein termed the S-CIE) in the Late Sinemurian O. oxynotum ammonite Biozone (~194 Ma) of eastern England (Fig. 2). The S-CIE reflects a perturbation to the whole exchangeable carbon reservoir because terrestrially-derived organic material (the palynomorph concentrate) and marine carbonate exhibit the same excursion (Fig. 2). The relatively brief record of L. variabile together with the transient acme of Classopollis classoides and the negative S-CIE is highly suggestive of a major climate-warming-driven biogeochemical perturbation, such as a carbon injection event, at ~194 Ma, and indicates that Jurassic climates were relatively susceptible to significant and transient change. The level of the S-CIE can be confidently delineated by the range and acme of L. variabile. The S-CIE shares many characteristics with the global negative CIE event at the PETM, a phase of abnormally high global temperatures coincident with a peak in the apparently thermophilic/eutrophic dinoflagellate cyst genus Apectodinium. The S-CIE also shares similarities to negative carbon isotope excursions at the T-OAE and OAE 1a, which are other major phases of global warming.

The S-CIE has so far only been recorded from a single succession in eastern England. However, the magnitude and remarkable synchronicity of the geochemical and palynological data from the Copper Hill Borehole indicate that the S-CIE probably represents a significant environmental change event. Eastern England is known to have been within an extensive, open seaway during the Early Jurassic (Coward et al., 2003), and hence may be representative of a large part of the Earth system at this time. It is considered that the marine and terrestrial geochemical and palynological signals documented here are not attributable to local factors, nor are they a result of background noise or oscillations in the carbon cycle. However it is fully acknowledged that more sections need to be studied to test our hypothesis. These should include more complete successions and those from localities outside Europe in order to verify this potentially important, apparently global, palaeoenvironmental change event.

Acknowledgements

The input of James B. Riding was completed under a BGS Individual Merit project entitled Global Jurassic dinoflagellate cyst palaeoecology and its applications. The authors sincerely thank Ian C. Harding and Robert A. Fensome for their constructive and perceptive comments on earlier drafts. Martin J. Head and an anonymous referee provided very helpful reviews of the manuscript. Sev Kender, Melanie J. Leng and James B. Riding publish with the approval of the Executive Director, British Geological Survey (NERC).

Appendix 1

This appendix lists all valid palynomorph taxa below generic level which are mentioned in this contribution with full author citations. The palynomorphs are listed alphabetically within three groups.

Dinoflagellate cyst:

Liassidium variable Druge, 1978

Gymnospermous pollen:

Araucariaeacites australis Cookson, 1947
Ceratopsidinae macraverrucosus (Thiergart, 1949) Schulz, 1967
Classopollis classoides (Pflug, 1953) Pocock and Jansonius, 1967
Perinopollis elastoides Couper, 1958
Vitreisporites pallidius (Reissinger, 1950) Nilsson, 1958

Pteridophyte spores:

Auritulinisporites scanicus Nilsson, 1958
Cibotiumspora juriensis (Balme, 1957) Filatoff, 1975
Concavissimisporites verrucosus Delcourt and Sprumont, 1955
Coronatispora valdensis (Couper, 1958) Dettmann, 1963
Cyathidites australis Couper, 1953
Cyathidites minor Couper, 1953
Gleichenidites senonicus Ross, 1949
Ischyosporites variegatus (Couper, 1958) Schulz, 1967
Kraeuselsisporites reissingeri (Harris, 1957) Morbey, 1975
Lepolepidites rotundus Traul, 1968
Lycospora pusilla (Ibrahim, 1932) Schopf et al., 1944
Neorastraictris gristhorpsis (Couper, 1958) Traul, 1968
Osmundacidites wellmanii Couper, 1958
Retiritrites austroclavatidites (Cookson, 1953) Döring et al., 1963
Sestrosporites psauloevelatus (Couper, 1958) Dettmann, 1963
Todisporites major Couper, 1958
Todisporites minor Couper, 1958
Tripartites vetustus Schelm, 1950
Uvaespores argenteiformis (Bolkhovitina, 1953) Schulz, 1967

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