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Methane seeps on an Early Jurassic dysoxic seafloor

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ABSTRACT

The rhythmically bedded limestone–marl–shale succession of the Blue Lias Formation (Lias Group, Early Jurassic age) of Kilve in Somerset (SW England) preserves a suite of large conical concretions that formed around methane seeps. These are 1–2 m high, and elliptical in plan (axes 2–4 m), with an outer limestone shell forming the flanks of the cone. The cone flank is composed of micritic carbonate (20–30 cm thick), which locally includes sheets and pods of intraclasts and bioclasts. The cycle-forming limestone beds of the host strata are composed of dark grey micrite with carbon-isotope values ($\delta^{13}C$=0.6 to 0.8‰) consistent with carbon sourced from a mixture of seawater and by sulphate reduction, and oxygen-isotope values ($\delta^{18}O$=−6‰) suggesting some degree of later diagenesis. The pale grey micrite that forms the sides of the mounds includes three-dimensional ammonites and intraclasts, and thus cemented close to the sediment–water interface prior to compaction. The mound-forming carbonate is markedly isotopically light with respect to carbon, but not with respect to oxygen ($\delta^{13}C$=−24.3 to −26.4; $\delta^{18}O$=−2 to −3.5‰). The isotope signature indicates that cements were probably derived from a mixture of sources that included biogenic methane. The intraclasts within the limestone suggest that syn-depositional physical brecciation and mixing of cements had occurred, and thus mixing of methane rich-fluids with the overlying surface waters is likely also to have occurred. The relatively heavy oxygen-isotope values may be indicative of anaerobic oxidation of methane. The mound-bearing interval of the Blue Lias Formation is benthos-poor and comprises predominantly laminated black shales, characteristic of poor bottom water oxygenation. The largest of the mounds is however, capped with fossiliferous breccias. Thus the mounds either formed benthic islands that elevated the biota into an oxic zone or, alternatively, they may have supported a chemotrophic community. Although cold seep deposits have been documented previously they are still comparatively rare. This example is one of the oldest in Europe, and is unusual amongst described ancient seeps in preserving relief that extended above the ancient seafloor.

1. Introduction

At the present day, chemosynthesis occurs through a broad range of depths, latitudes, and settings (Campbell, 2006) that include seafloor hydrothermal vents (Lonsdale, 1977), cold hydrocarbon seeps (Paull et al., 1984), and around carrion (Allison et al., 1991; Dahlgren et al., 2006) and wood-fall (Distel et al., 2002). The ecosystems developed around these sites are not fuelled directly by energy derived from photosynthesis, but from a range of alternative or derivative chemical pathways. Biomass production is facilitated by prokaryotes that derive energy from the oxidation of methane or sulphides in fluids emanating from the vents, seeps or carrion. This can then be consumed by a diverse array of metazoa, some of which may even be symbiotic with the prokaryotes themselves. Fossilised vent, seep, and carrion fall localities with preserved biota do occur, and have recently been reviewed by Campbell (2006). Her review largely excludes carrion and wood-falls, but documented 56 examples of vents and seeps ranging in age from Pleistocene to Archean. The majority (46) were cold seeps.

Here we describe a cold seep deposit from the upper (Sinemurian) part of the Blue Lias Formation of Somerset, UK. The biota associated with the largest mound includes ammonites, bivalves, foraminiferans, and sparse crinoid ossicles. Previous work has highlighted the unusual conical structure of these features (Whittaker and Green, 1983, p.71) and suggested that they were mud volcanoes resulting from over-pressuring of the underlying Triassic strata (Cornford, 2003). We present carbon and oxygen-isotope data that these mounds were exuding hydrocarbons, probably methane, at the seafloor at the time of their formation. This is one of the oldest documented cold seep deposits in Europe, second only to the Carboniferous Iberg Reef of the Harz mountains (Peckmann et al., 2001).

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2. Geological setting

The Early Jurassic aged strata of southern Britain (Lias Group) were deposited in a series of small extensional basins, and crop out in a northeast/southwest belt extending from Yorkshire to Dorset (Fig. 1). The marine Blue Lias Formation (Cox et al., 1999) overlies the Rhaetian Lilstock Formation of the Penarth Group of mostly marine origin (e.g. see Hesselbo et al., 2004; Allison and Wright, 2005 and references therein). The Penarth Group sits on top of older Triassic terrestrial deposits, and the succession records progressive Late Triassic to Early Jurassic transgression.

The cliffs and foreshore of the coastline between Hinkley Point and Watchet in Somerset, UK, expose an almost complete section of the Hettangian to Sinemurian stages represented by the Blue Lias Formation (Fig. 2). These strata were deposited in a subsiding basin which subsequently underwent basin inversion in the Tertiary (Peacock and Sanderson, 1999; Glen et al., 2005). The formation in SW Britain is composed of a series of rhythmically alternating black and grey shales with marls and diagenetically enhanced limestones (Hallam, 1960; Palmer, 1972; Whittaker and Green, 1983; Paul et al., in press). The black shales are laminated, organic-rich, have sharp bases, and are largely benthos-poor. They typically grade upwards into grey bioturbated shales and then marls and limestones. The latter form persistent concretionary, lenticular to tabular mudstone to wackestone bands and are commonly capped with packstone lenses or stringers. Cycle thickness varies but is typically of the order of 1 m with cycle components recording variations in bottom water oxygenation (Sellwood, 1970). Time series analyses of coeval strata in Dorset have demonstrated that the cycles were a response to orbitally forced climate change (Weedon, 1986; Waterhouse, 1999). Correlative cyclic sediments of Yorkshire have been attributed to precessional, obliquity, and eccentricity orbital forcing (Van Buchem et al., 1994; Hesselbo and Jenkyns, 1995).

3. Mound description

The seep mounds are exposed on the foreshore east of an abandoned cliff-top observation station at grid reference ST 1510E 4462N. They occur in the *Arietites bucklandi* Zone (Sinemurian) of the Blue Lias Formation, around beds 182 to 186 of Whittaker and Green (1983) and just above a notable shale-rich part of the section (the 'Kilve Shales' of Palmer, 1972). Additional occurrences of the mounds at the same stratigraphic level at Hinkley Point, some ~5 km to the east, are alluded to by Whittaker and Green (1983, p.71), p.71).

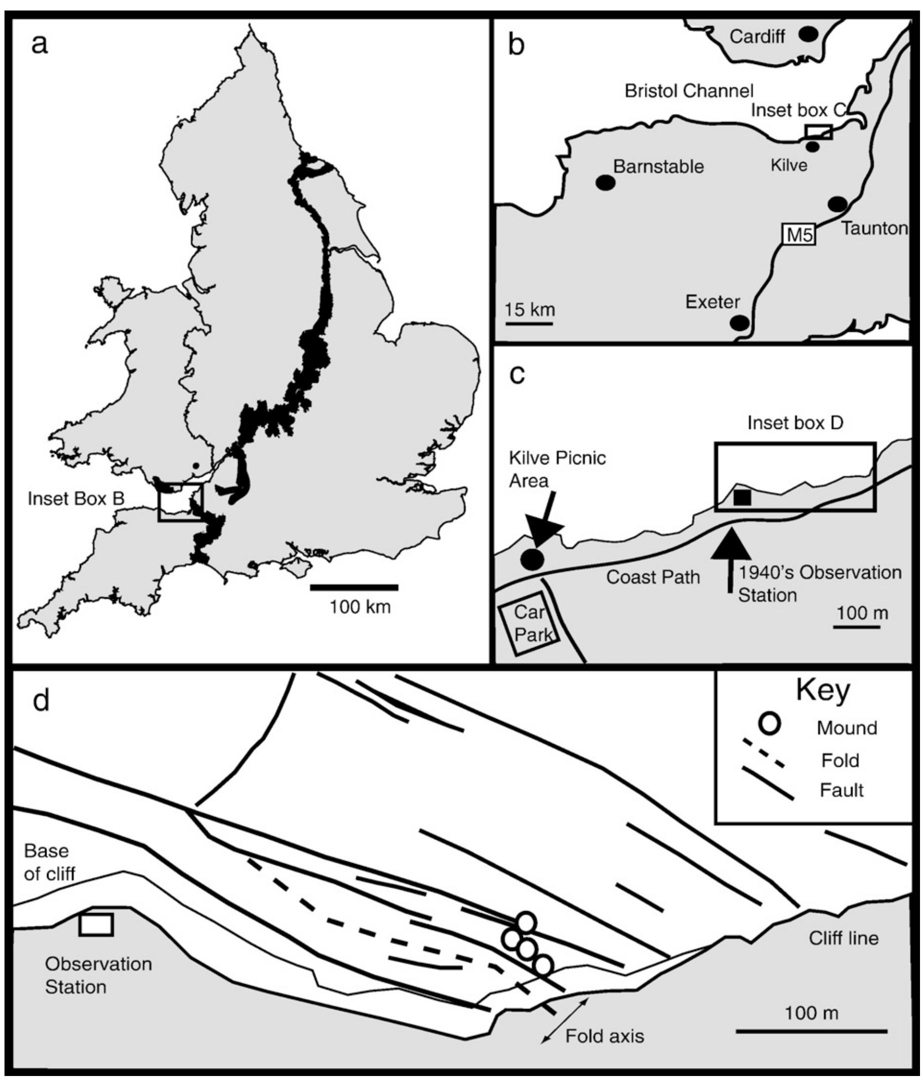

Fig. 1. Location maps, land above high-water mark is shaded. a, outcrop (black) of the Lias Group in England and Wales. b, area around Kilve in Somerset. c, location of the seep mounds on the Kilve foreshore east of the picnic area and coastal lookout station. d, location of seep mounds in relation to faults and fold axes (after Glen et al., 2005).

	Stages	Zones	Bed Numbers (Whittaker & Green, 1983)	Lithostratigraphy (Palmer, 1972)	Lithostratigraphy (Cox et al., 1999)
Early Jurassic	Sinemurian	*Echioceras raricostatum*			Charmouth Mudstone Formation
		Oxynoticeras oxynotum			
		Asteroceras obtusum			
		Caenisites turneri			
		Arnioceras semicostatum	209	Hellwell Marls Doniford Shales Quantocks Beds	Blue Lias Formation
		Arietites bucklandi	146	Kilve Shales	
	Hettangian	*Schlotheimia angulata*	80	Blue Lias	
		Alsatites liasicus	43	St. Audrieís Shales	
		Psiloceras planorbis	14	Aldergrove Beds	

Fig. 2. Biostratigraphy and lithostratigraphy of the Blue Lias (based on Cox et al., 1999).

3.1. Morphology

There are four large coniform mounds (Cornford, 2003) with basal diameters of 3–4 m and heights of 1–1.5 m (Figs. 1d and 3) and around 10 smaller (<1 m diameter) concretionary masses. The four larger mounds form a crude straight line. The most northerly mound is offset from the other three by a small fault (Fig. 1d). The smaller concretionary masses occur stratigraphically about 1 m above the base of the mounds.

The outer surfaces of the larger mounds are composed of micritic carbonate that is pale grey-brown when weathered but blue-grey when fresh. The apex of mound 1 (Fig. 3b) has a small crater which is lined with bioclastic and pebble-cobble sized intraclasts (Fig. 4a). The matrix around the clasts has an expansive "cottage cheese" fabric in places. The intraclasts are rounded and heavily iron-stained when weathered. Recent erosion of the northern flank of mound 2 has breached the 30 cm layer of limestone and exposed an underlying black shale (Fig. 3c).

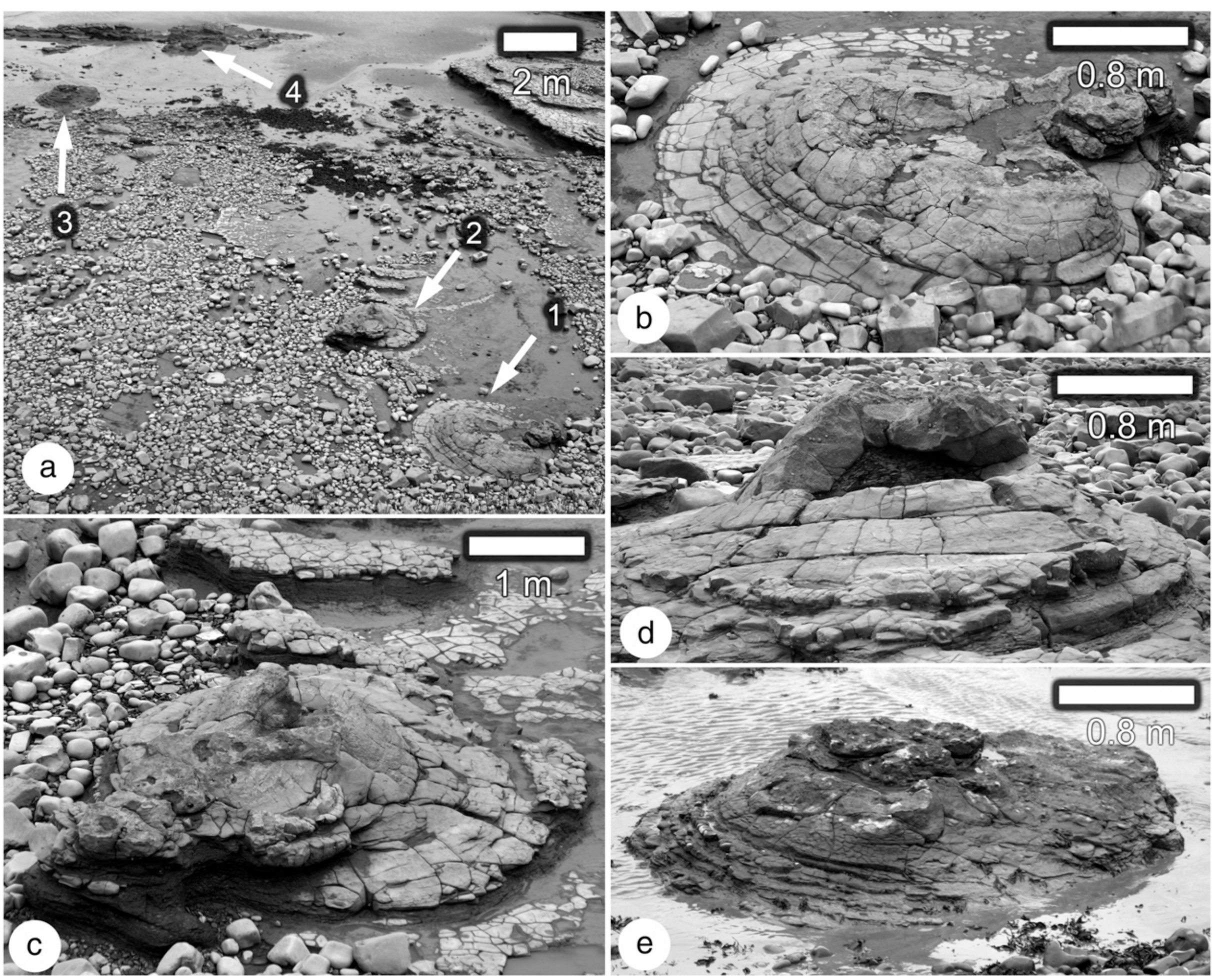

Fig. 3. Seep mounds on Kilve foreshore (ST 1510E 4462N). a. Overview looking north from the cliff-top 100 m east of the abandoned observation station with mounds numbered 1–4. b, close up of mound 1 (the most southerly). Mound is about 1 m high with prominent crater at the apex. c, close up of mound 2. Mound is 1.5 m high with brecciated zone on the cone flank (lower left of figure). d, view of mound 2 looking south, a recent erosional breach has exposed the shale core of the mound. e, close up of mound 3.

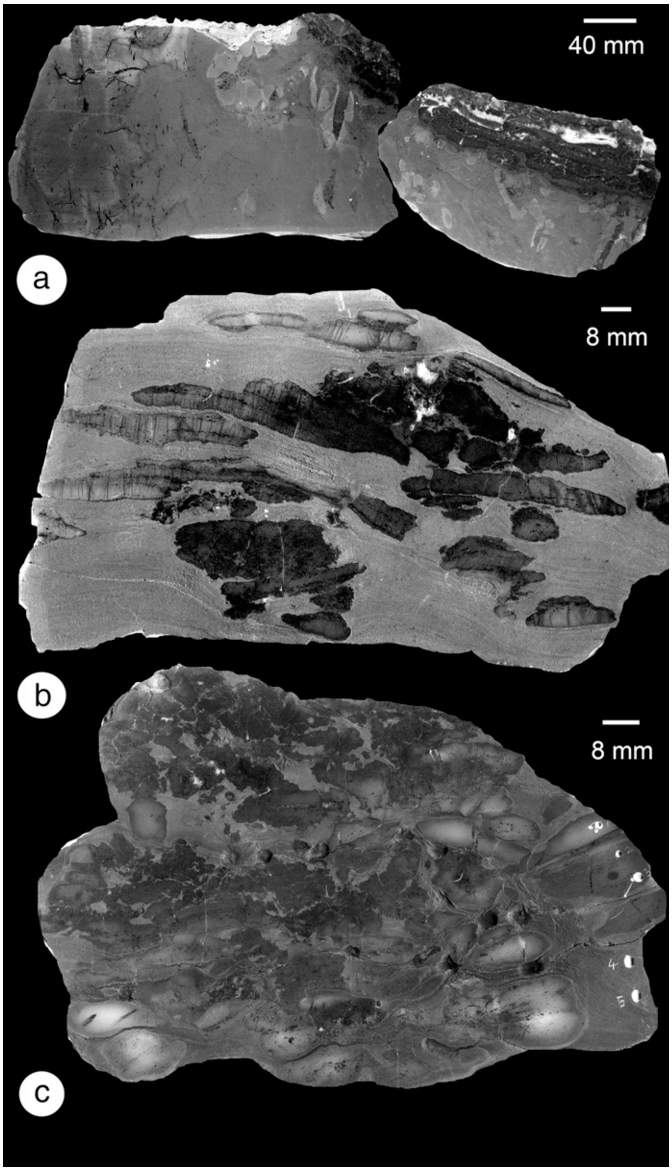

Fig. 4. Mound and concretionary carbonate. a, slabbed block of the crater surface of mound 1. Upper surface in picture was uppermost on mound. Note brecciated fragments and dark laminated crust. b and c, slabbed blocks of smaller concretions, note abundant partially re-oriented smaller concretions within the larger concretionary block. Re-orientation of the smaller concretions is evidenced by the variable orientation of lamination. This most likely occurred during compaction before the enclosing concretion had formed.

Septarian fractures cut through both the outer limestone and the crater-lining carbonate.

The smaller concretionary masses are apparently randomly distributed around the larger mounds, and vary in size from 40 cm to 1 m in diameter and are no more than 40 cm thick. They are blue-grey when weathered but grey-black when freshly exposed and are composed of a fine-grained matrix with pebble-sized intraclasts. The intraclasts are only in these concretionary masses and are not in the adjacent host shale. Lamination can be traced from one clast to another, indicating very limited movement after lithification (Fig. 4).

3.2. Biota

The rhythms of the Blue Lias clearly record variations in benthic oxygenation (Sellwood, 1970). The laminated black shales include the remains of the free-swimming ammonites but are devoid of benthos. The grey shales and limestones are bioturbated and thus evidence some seafloor oxygenation, but shelly benthic taxa are rare in this part of the Blue Lias. The mounds are largely devoid of biota except for within the crater at the top of mound 1. This contains thin stringers and sheets of medium to coarse-grained bioclastic debris, abundant small (<1 cm) ammonites, foraminiferans (*Involutina*), crinoidal debris and sparse bivalves (Fig. 5). The ammonites are whole and preserved three-dimensionally in pale red-brown calcite, whereas the crinoids are completely disarticulated. Bivalves are extremely rare and none have been found which are sufficiently well preserved as to be identifiable (Fig. 5). The bivalves have large body cavities and although this character is common in chemosymbiotic forms, it is also shared with other trophic groups. Equally the isotopic chemistry of bivalve shells is not a reliable indicator of trophic status as shell carbonate can be sourced from seawater as well as metabolic bi-products (Allison et al., 1995). There is thus little evidence in favour or against the possibility that the mounds supported a chemotrophic community.

3.3. Isotope geochemistry

Stable carbon and oxygen-isotope data ($\delta^{13}C$ and $\delta^{18}O$) were generated from two suites of samples. The first set (Fig. 6, Table 1) includes whole-rock samples of shale and limestone collected approximately every 20 cm over the 5 m of succession that hosts the mound-bearing levels. The second set of samples was taken from a polished slab of the limestone forming the crater of mound 1 and includes—lithoclasts, crustose cements, and septarian fissure fills (Fig. 7, Table 1). Samples from the host succession were collected in the field with a battery-powered hand-operated drill, using an 8 mm diameter masonry drill bit. Powder was collected using plastic bags held under the drill bit. Samples collected in the lab were drilled out

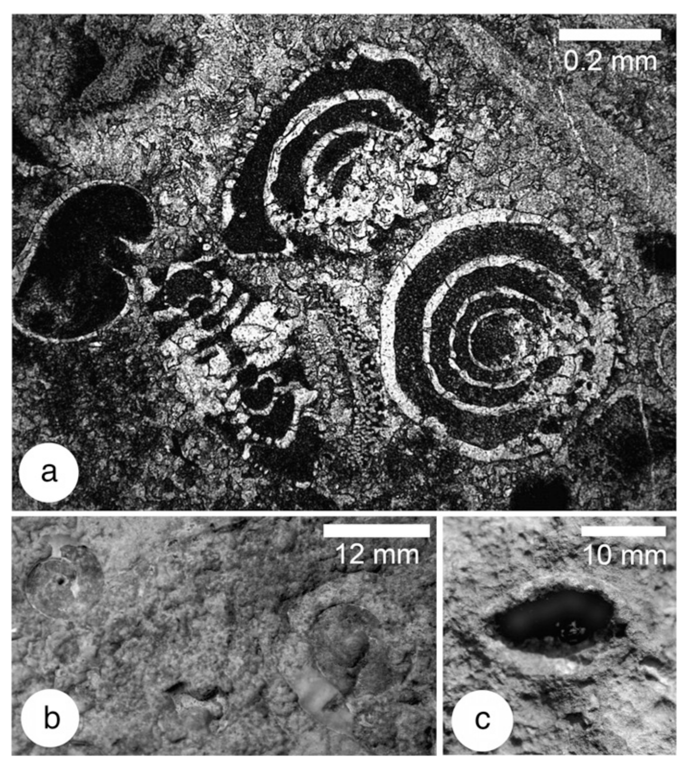

Fig. 5. a, Thin-section photomicrograph showing variably oriented individuals of the foraminifera *Involutina*. b, small ammonite overgrown by calcitic crust. c, cross-section of bivalve lined with sparry calcite.

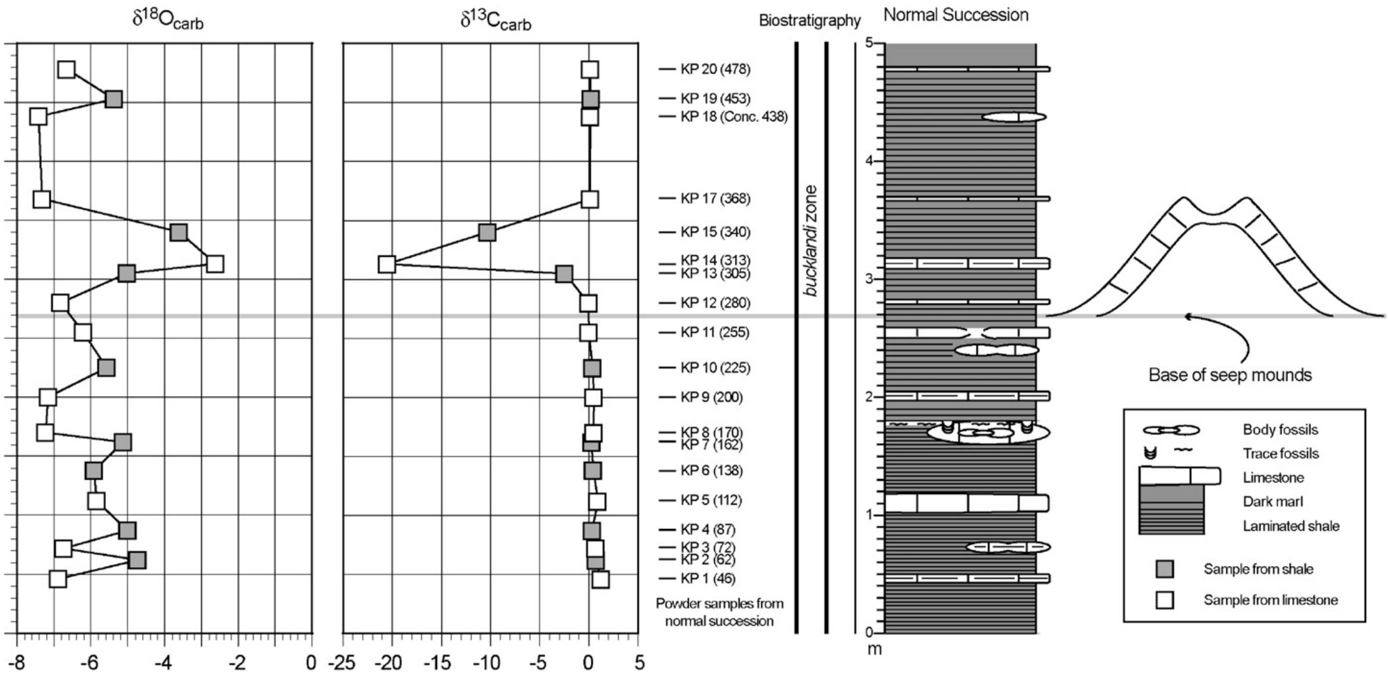

Fig. 6. Whole rock isotopic composition ($\delta^{13}C$ and $\delta^{18}O$) through the mound-bearing part of the Blue Lias Formation with sample spacing of approximately 20 cm (data from Table 1).

from a polished slab using a small hand-held foot-operated drill. Samples were analysed isotopically for $\delta^{13}C$ and $\delta^{18}O$ using a VG Isogas Prism II mass spectrometer with an on-line VG Isocarb common acid-bath preparation system. Samples were first cleaned using hydrogen peroxide (H_2O_2) and acetone (((CH_3)2CO) and dried at 60 °C for at least 30 min. In the instrument they were reacted with purified phosphoric acid (H_3PO_4) at 90 °C. Calibration to PDB standard via NBS-19 is made daily using the Oxford in-house (NOCZ) Carrara marble standard. Reproducibility of replicated standards is usually better than 0.1‰ for $\delta^{13}C$ and $\delta^{18}O$.

The $\delta^{13}C$ values of the samples through the enclosing host succession (Fig. 6, Table 1) vary from a background level of around 0 to 1‰ and decrease to −20‰ at the stratigraphic level of the mounds (Table 1, Fig. 6). The $\delta^{18}O$ values of the same samples vary from a background level of −5 to −7 (with the limestones being lightest) but increase to −2 to −3‰ at the mound level. There is a clear covariance between the heavier oxygen isotopes and lighter carbon isotopes at the level of the mound (Fig. 8).

The limestone forming the crater is texturally heterogeneous (Figs. 4 and 7) and includes—medium and pale grey micrite and micritic intraclasts, dark brown microspar crusts, white, cream, or straw coloured spar, and dark grey micrite that infills fractures. Samples 11, 12, 14 and 15 (Fig. 7) from the grey micrite and micritic intraclasts have $\delta^{13}C$ values of −22 to −27 and $\delta^{18}O$ values of −4 to −5. The samples of the various crusts and spar-fillings have isotopic values of −4 to −10 for $\delta^{13}C$ and −5 to −8 for $\delta^{18}O$.

4. Interpretation

4.1. Origin of the mounds

The coniform structure of the mounds is striking and is apparently unique to this level in the Blue Lias. The presence of intra-formational conglomeratic clasts in the crater of mound 1, and on the flanks, suggests that the mounds formed a topographic structure on the seafloor, and are thus syn-depositional. It has been suggested (Cornford, 2003) that they formed in a line that may be related to sub-surface faulting. However, we argue that this lineation is simply the result of limited outcrop on a relatively uniformly dipping surface (i.e. is along strike). The Blue Lias that hosts the mounds is composed of laminated shale and limestone with a sparse benthic biota (the concretionary limestone 1 m below the mounds exhibits some trace fossils), and this indicates deposition in a largely oxygen-deficient system. The mounds are also largely devoid of benthos except mound 1 where the presence of bivalves, crinoids and foraminifera indicates some benthic oxygenation. This could be because the mound formed a benthic island that penetrated above a chemocline, or it could be because mound 1 is larger, was longer lived, and colonised during a brief phase of benthic oxygenation.

Cementation of the mounds preserves the three-dimensionality of ammonites and thus pre-dates burial compaction. The carbonates flooring the crater on mound 1 are clearly polyphasic and include pebble-cobble sized intraclasts as well as various brown crusts and spar fills (Figs. 4 and 7). The C and O isotope values of the crusts and spar are similar to that of typical Early Jurassic shales and limestones of the region (Fig. 6; also Hesselbo et al., 2007), indicating that the carbonate was largely sourced from seawater (e.g. Hudson, 1977). The grey matrix and intra-formational conglomerates, however, are strongly negative with respect to $\delta^{13}C$ with values of between −25 and −27‰. Marine systems include a variety of carbon sources (Fig. 9) and the isotopic composition of typical authigenic carbonates often reflects some degree of mixing of these potential contributors (see Campbell et al., 2002; Peckmann and Thiel, 2004; Campbell, 2006).

The isotopic values recorded for the grey matrix and intraclasts (Fig. 7, Table 1) are similar to those that would be expected for non-methanogenic anaerobic degradation of organic matter such as through sulphate reduction (Campbell, 2006). However, if this were the case the cements would represent a very pure phase with minimal contribution of carbon from the overlying seawater. Given that the cements formed very close to the sediment–water interface and were even subject to erosion during intraclast formation it seems unlikely that non-methangenic anaerobic degradation of organic matter could be the sole carbon source. It is much more likely that the grey micrites and intraclasts of the mound carbonate include carbon sourced from

Table 1
Whole rock carbon and oxygen isotopes (carbonate)

Height	Sample	$\delta^{13}C$	$\delta^{18}O$	Notes
Sample set 1				
Height (cm), see Fig. 6				
46	KP1	1.219	−6.889	Limestone
62	KP2	0.728	−4.725	Shale
72	KP3	0.673	−6.732	Limestone
87	KP4	0.312	−5.007	Shale
112	KP5	0.903	−5.840	Limestone
138	KP6	0.442	−5.913	Shale
162	KP7	0.281	−5.121	Shale
170	KP8	0.481	−7.221	Limestone
200	KP9	0.504	−7.154	Limestone
225	KP10	0.352	−5.567	Shale
255	KP11	−0.013	−6.210	Limestone
280	KP12	−0.025	−6.818	Limestone
305	KP13	−2.443	−5.016	Shale
313	KP14	−20.504	−2.612	Limestone
340	KP15	−10.303	−3.608	Shale
360	KP16	−0.071	−7.022	sediment matrix to pebble bed
368	KP17	0.125	−7.315	Limestone
438	KP18	0.143	−7.409	Limestone
453	KP19	0.219	−5.363	Shale
478	KP20	0.130	−6.656	Limestone
Sample set 2				
Height (mm), see Fig. 7				
74	KL3b/1	−3.240	−7.901	Brown mud above crust
67	KL3b/2	−10.842	−6.708	Straw brown spar in crust
60	KL3b/3	−9.076	−6.394	Dark brown sediment/cement in crust
54	KL3b/4	−7.262	−5.471	Dark brown sediment/cement in crust
56	KL3b/5	0.389	−5.267	Straw brown spar in crust
50	KL3b/6	−3.579	−5.782	Dark brown sediment/cement in crust
45	KL3b/7	−2.567	−5.487	Dark brown sediment/cement in crust
41	KL3b/8	−7.067	−6.880	Dark brown sediment/cement in crust
35	KL3b/9	−2.674	−6.469	Grey sediment below crust
30	KL3b/10	−13.077	−5.311	Grey sediment below crust
23	KL3b/11	−26.119	−4.161	Grey sediment below crust
18	KL3b/12	−21.649	−4.666	Grey sediment below crust
13	KL3b/13	−11.331	−5.205	Grey sediment below crust (dyke/septaria)
5	KL3b/14	−22.692	−4.308	Grey sediment below crust
0	KL3b/15	−23.493	−4.292	Grey sediment below crust
N/A	KL2/1	−21.032	−3.324	Pebble
N/A	KL2/2	−19.087	−3.618	Pebble
N/A	KL2/3	−15.718	−3.983	Pebble
N/A	KL2/4	−2.143	−6.555	Matrix
N/A	KL2/5	−0.139	−7.384	Matrix

Sample set 1 taken from host stratigraphy at a 20 cm sample spacing (Fig. 6). Sample set 2 taken from apex of limestone layer that forms mound 1 (KL3; Figs. 4a, 7) and other concretionary masses (KL2; Fig. 4c).

some form of methane. This would imply that the carbonate precipitated from the action of either aerobic or anaerobic methanotrophic bacteria. Anaerobic methanotrophy is an unlikely process in this context because it would likely have led to limestone dissolution (Paull et al., 1992).

Methane can be derived thermogenically as a product of hydrocarbon maturation ($\delta^{13}C$ values of between −25 and −50) or biogenically during microbial respiration ($\delta^{13}C$ values of <−50; Paull et al., 1992; Campbell et al., 2002; Campbell, 2006). Both sources could have potentially supplied methane for mound formation at Kilve.

The deeply underlying Carboniferous rocks could have generated thermogenic gas, and the underlying organic-rich shales of the Blue Lias (Kilve Shales of Palmer, 1972) could have sourced biogenic gas. The $\delta^{13}C$ values from the grey micrite and lithoclasts in the mound carbonate (Fig. 7, Table 1) are closer to those of a thermogenic, relatively deep-seated source. However, we regard this as unlikely for the following reasons. (1) There is no evidence that the mounds aligned with any potential conduit for deeply sourced fluids. (2) The mounds occur only at a single stratigraphic level, above the potential biogenic methane source beds. (3) If the cements were sourced by carbon derived from thermogenic methane then the isotopic values of the grey micrites and lithoclasts (−25 to −27‰) would indicate that they were largely or solely derived from this source. Given that the cements formed close to the sediment–water interface and include erosional features it is likely that the cements would also incorporate carbon from different sources such as from seawater and from sulphate reduction.

A biogenic source for the methane is therefore most likely and this would not require the presence of hitherto unknown syn-depositional tectonics or deep-seated tectonic structures. The consumption of the biogenic methane by microbes released the carbon for subsequent incorporation into carbonate minerals.

4.2. Isotope stratigraphy of host rocks

The $\delta^{13}C$ of carbonates sampled from the shale and limestone on the foreshore between the mounds is ~1 to 2‰ lighter than those from oysters in the Blue Lias (Korte and Hesselbo, unpublished data) and thus probably includes carbonate sourced from seawater with a minor diagenetic component. However, at the stratigraphic level of the mounds there is a pronounced excursion to negative carbon-isotope values similar to those of the grey micrite and intraclasts in the mound carbonate. Very similar observations have recently been reported for a Late Jurassic cold seep in SE France

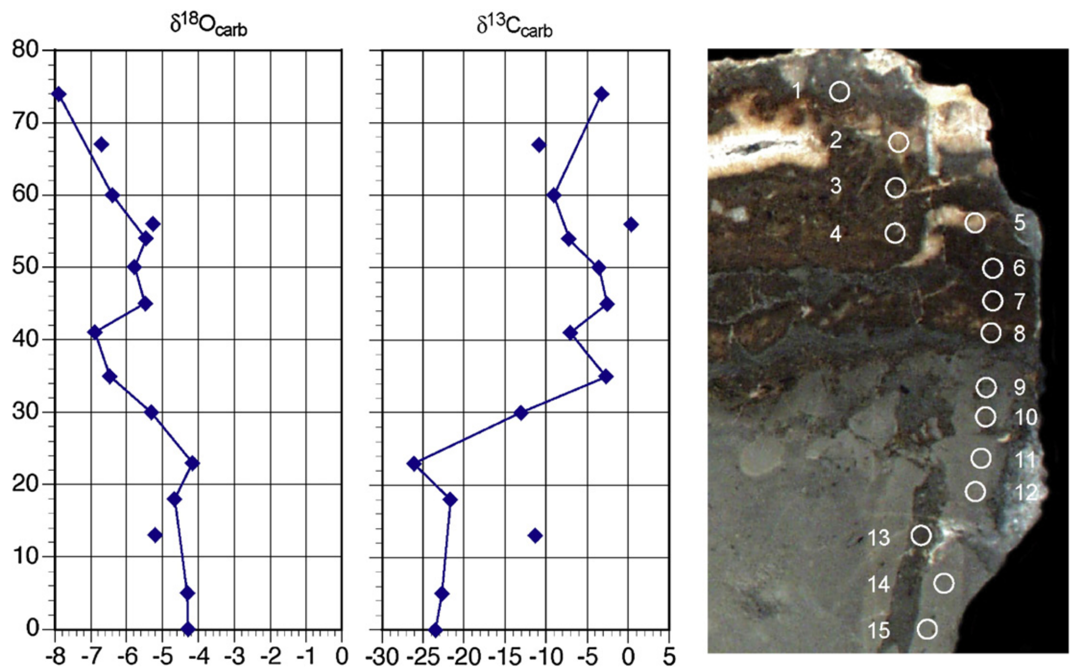

Fig. 7. δ^{13}C and δ^{18}O values of samples taken from polished slab of limestone crust forming the crater at the apex of mound 1. Sample points are indicated by white numbered circles.

(Louis-Schmid et al., 2007). In the case of the Blue Lias, the isotope anomaly occurs in laminated shales and limestones which bear no textural, morphological, or biotic evidence of methanotrophy. This could indicate that either the bi-products of methanotrophy or the methane exuded from the mounds were dissolved within the water column.

Methane oxidation could have occurred in the water column at the interval coinciding with the isotopic excursion, indicating euxinic conditions with sulphate reduction occurring below the oxycline in a stratified water-body. This is supported by the presence of lamination in the shales and the overall paucity of benthos and is certainly plausible in an epicontinental sea (Allison et al., 1998; Allison and Wright, 2005; Allison and Wells, 2006). However, the distinctive biota preserved in the crater on mound 1 includes nektonic ammonites and benthic crinoids and sparse bivalves and thus indicates benthic oxygenation. This apparent contradiction with the isotopic data could be accommodated by the presence of a variable oxycline which was periodically removed or depressed to the seafloor. The low abundance of shelly benthos suggests that such depression was brief and did not facilitate prolonged colonization.

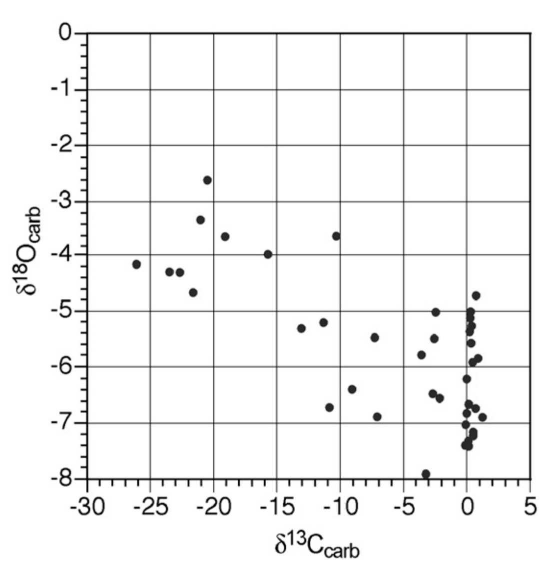

Fig. 8. Cross plot of δ^{13}C and δ^{18}O values of all samples (Table 1). Note covariance of δ^{18}O enrichment with δ^{13}C depletion.

The δ^{18}O of the carbonates co-varies with that of δ^{13}C (Fig. 8). Those samples which have the most negative δ^{13}C values are also the most positive with respect to δ^{18}O. This is the opposite of what would be expected from most diagenetic processes (Corfield, 1995).

The growth of concretionary carbonate can extend for long periods (Raiswell and Fisher, 2000, 2004) and include bicarbonate ions sourced from diverse and multiple pore-fluids (Hudson et al., 2001). The possibility that the anomalously positive oxygen-isotope values associated with the most negative carbon isotopes is due to some combination of carbonates deposited by multiple generations of pore-fluids cannot be discounted. However, it is possible that the most positive oxygen values are a result of methanotrophy.

Sulphate-reducing bacteria preferentially utilize sulphates with the lightest oxygen isotope leaving a residual pool of sulphate enriched in δ^{18}O (Zak et al., 1980; Böttcher et al., 1998a,b, 1999, 2004). The magnitude of fractionation depends upon a variety of factors including —reaction rate, oxidant concentrations, and microbial community structure (Jørgensen, 1979; Berner, 1980; Boudreau and Westrich, 1984; Aharon and Fu, 2000). The bicarbonate produced by these bacteria and precipitated in diagenetic concretions could therefore preserve oxygen-isotope values that were influenced by sulphate reduction. The positive excursion of δ^{18}O combined with the strongly negative excursion of δ^{13}C could indicate anaerobic methanotrophy and sulphate reduction occurring within a few centimetres of the seafloor.

5. Conclusions

The earliest Sinemurian aged Blue Lias Formation of Kilve, west Somerset, preserves a suite of conical mounds well exposed on the coastal foreshore. Isotopic analyses of mound carbonates and stratigraphically equivalent limestone beds reveal a strong covariance between δ^{13}C and δ^{18}O. Progressive depletion of δ^{13}C is accompanied

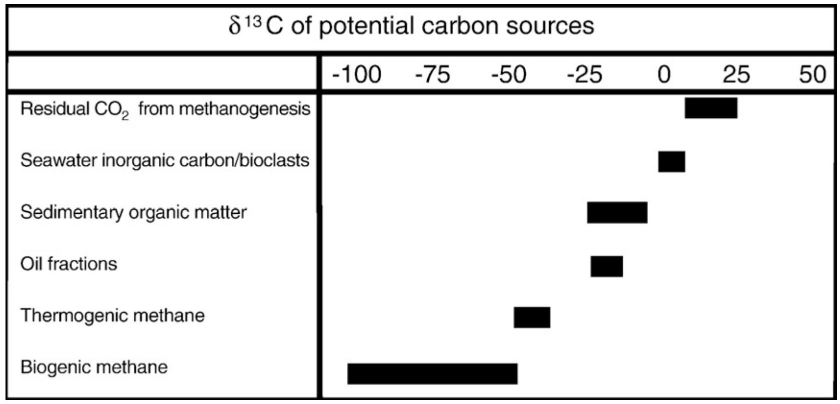

Fig. 9. $\delta^{13}C$ values of potential carbon sources in marine systems (modified from Campbell et al., 2002; Campbell, 2006).

by enrichment in $\delta^{18}O$ and is indicative of microbial anaerobic methanotrophy and sulphate reduction. The source methane is inferred to have been of shallow biogenic origin, derived from methanogenesis occurring within underlying organic-rich muds.

Vents and seeps in oxygenated waters commonly support metazoa that can include chemosymbiotic forms (Campbell, 2006). Most of the bioclasts preserved on the mounds are fragmented and disarticulated and cannot be identified. As yet there is thus little evidence for or against the possibility that the mounds supported a chemotrophic community.

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