Uniquely extensive soft-sediment deformation in the Rhaetian of the UK: Evidence for earthquake or impact?

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Abstract

The lower part of the Cotham Member in the Penarth Group (latest Triassic, Rhaetian) of the UK incorporates a uniquely extensive metre-scale horizon of soft-sediment deformation. Interpreted as a seismite, it shows evidence for only a single seismic event even at its thickest development. It is recorded from more than forty sites across at least eight discrete sedimentary basins covering >250,000 km², and originally must have covered a still larger area. Such a widespread horizon of soft-sediment deformation, unique for the UK Phanerozoic and implying a seismic event of exceptional magnitude, is difficult to account for by conventional terrestrial mechanisms. Contemporaneous volcanism in the Central Atlantic Magmatic Province (CAMP) was too far distant to cause the deformation, and the tectonic setting of the region was not conducive to earthquakes on this scale. Slump fold long axes suggest an epicentre broadly in the southern Irish Sea or St. George’s Channel. Impact of a km-scale asteroid here potentially could produce the observed sedimentological effects across the UK, but any late Triassic impact structure would now be concealed by a km or more of younger strata. At its thickest development, in Northern Ireland, the seismite is succeeded by a rip-up breccia and hummocky- and wave-rippled cross stratification. These facies, and their position immediately above the seismite, are consistent with the effects of a tsunami arising directly from the seismic event. Tentative evidence for a tsunami of this age has also been reported from southern France. The putative tsunami in Northern Ireland is succeeded by a desiccation-cracked hiatus which may correlate with a similar hiatus truncating the seismite at sites in southern England. The hiatus in southern England correlates closely with a δ¹³C isotope excursion that has been traced from eastern Europe across to western North America and is associated with significant biotic changes. The ultimate cause of the seismite and associated tsunami remains unclear. No impact crater of appropriate age or location is currently known and other evidence for impact at this time is at best equivocal. It is considered here that impact of a km-scale asteroid may have caused the observed sedimentological effects in the Lilstock Formation across the UK area, but was not necessarily a significant contributory factor in the generation of either the isotope excursion or of the biotic changes through the Triassic–Jurassic boundary interval.

Keywords: Seismite; Tsunamite; Triassic–Jurassic boundary

1. Introduction

The Triassic–Jurassic boundary interval was a period of major change in the history of life on Earth. Early geologists recognized the two geological systems as distinct on the basis of their contained fossils, these differences subsequently being attributed to one of the great mass extinctions in Earth history. The cause of these biotic changes, seen most strikingly in the marine succession (Hallam, 1990; Benton, 1991; Hallam, 2002),
has been much debated. Eustatic sea level change through Late Triassic and Early Jurassic times (Hesselbo et al., 2004; Hallam and Wignall, 2004), causing widespread benthic anoxia, may have affected the marine fauna (Hallam and Wignall, 1999; Wignall, 2001a). Massive volcanism associated with the Late Triassic to Early Jurassic Central Atlantic Magmatic Province (CAMP) (Wignall, 2001b) has also been invoked as a trigger for significant biotic and geochemical effects at this time (Hesselbo et al., 2002). Inevitably, the discovery of a massive meteorite impact coincident with the end-Cretaceous extinction (Alvarez et al., 1980) has led to claims and counter claims for an impact cause for other mass extinctions including that at the end of the Triassic. The end-Cretaceous impact remains the only one for which the current evidence is more than speculative, with a whole suite of sedimentary and geochemical phenomena diagnostic of impacts now recognized in association with this event.

This paper sets out the evidence for an apparently unique seismic event recorded in Rhaetian strata across the United Kingdom, its broad relationship to the biotic changes through the Triassic–Jurassic boundary succession, and possible causes of the resultant seismite. It expands on earlier work (Simms, 2003a,b) by incorporating new observations, additional published data, and a review of the evidence, worldwide, for bolide impact during the Triassic–Jurassic boundary interval.

2. The Penarth Group (Rhaetian) of the United Kingdom

The Penarth Group is a relatively minor (<15 metres thick) stratigraphic unit between the predominantly non-marine red-bed facies of the Mercia Mudstone Group below and the marine mudstones and other lithologies of the Lias Group above (Fig. 1), both of which may reach several hundred metres in thickness. The Penarth Group follows a roughly southwest–northeast outcrop pattern across England, between southeast Devon and northeast Yorkshire. Other minor outcrops include those to north and south of the Bristol Channel, in the Cheshire, Needwood and Carlisle basins, in the Lame–Lough Neagh Basin and Rathlin Trough in Northern Ireland, and very small outcrops in Scotland. Euryhaline conditions, established during deposition of the Blue Anchor Formation at the top of the Mercia Mudstone Group, continued through the ensuing Penarth Group before more stenohaline conditions developed early in the deposition of the Lias Group. The Penarth Group is remarkably consistent in thickness and facies throughout England, Wales and Northern Ireland. Dark pyritous mudstones and thin sandstones of the Westbury Formation, with a restricted quasi-marine fauna, are succeeded by paler, siltier mudstones, sandstones and calcilutitic limestones of the Lilstock Formation, containing both marine and non-marine fossils. In southern Britain the Lilstock Formation is divided into the siltstone- and mudstone-dominated Cotham Member below and the commonly more carbonate-rich Langport Member above. In northern England and Northern Ireland this bipartite division of the Lilstock Formation is less clear although there is still a sharp demarcation from the Westbury Formation below.

A conspicuous and widespread feature of the lower part of the Lilstock Formation, at a level a few metres below the first appearance of the Jurassic ammonite Psiloceras near the base of the Lias Group, is a metre-scale horizon of soft-sediment deformation which forms the main subject of this paper. It was first noted in several boreholes by Poole (Poole and Whiteman, 1966; Poole, 1969, 1977, 1978), who ascribed it to the effect of earthquake shock waves on poorly consolidated sediments. He immediately recognized its significance for correlation and it was subsequently identified and described at outcrop in the Bristol Channel (Whittaker, 1978; Mayall, 1983). This deformed bed remained little more than a curiosity until work began in earnest on assessing the suitability of the section at St Audrie’s Bay, on the north Somerset coast of the Bristol Channel, as a candidate Global Stratotype Section and Point (GSSP) for the base of the Hettangian Stage, and hence of the Jurassic System (Hallam, 1990; Warrington et al., 1994; Hesselbo et al., 2002, 2004; Hounslow et al.,
2004). At this site the deformed bed, located about 7 m below the first *Psiloceras* (Hodges, 1994), comprises a 1 metre thick horizon of soft-sediment deformation truncated sharply by an erosion surface penetrated by deep desiccation cracks (Fig. 2). A significant outcome of the investigations at St Audrie’s Bay was the recognition of a negative $\delta^{13}C$ excursion in the Triassic–Jurassic boundary interval, with a relatively abrupt and brief Initial Isotope Excursion succeeded, a few metres higher, by a more prolonged Main Isotope Excursion (Hesselbo et al., 2002). Detected also in Hungary (Pálfy et al., 2001), western Canada (Ward et al., 2001) and the southern USA (Guex et al., 2004), this appeared to have potential for intercontinental, and possibly even global, correlation. At St Audrie’s Bay the Initial Isotope Excursion identified by Hesselbo et al. (2002) occurs just above the erosion surface that truncates the seismite (Fig. 2). These excursions, attributed to the effects of volcanic gases and methane hydrate dissociation during eruption of the Central Atlantic Magmatic Province (CAMP) flood basalts (Pálfy et al., 2001; Hesselbo et al., 2002), appear to be closely associated with significant biotic changes across the Triassic–Jurassic boundary interval.

This raises the question of whether the seismite, the Initial Isotope Excursion and the biotic changes through the Triassic–Jurassic boundary interval might be causally linked. The latter two ‘events’ are certainly widespread, if not yet proven to be global in extent. Hence, if the seismite is linked to either or both of these events then it too might be expected to have an unusually wide distribution.

3. Distribution of the Lilstock Formation seismite

The observations and interpretation of Poole (1969, 1977, 1978; Poole and Whiteman, 1966) and Mayall (1983), that the soft-sediment deformation was triggered by seismic shock, are consistent with analogous

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Fig. 2. Correlation of the upper Penarth Group between some of the main sites discussed in the text. The section at Lavernock is based largely on Mayall (1983). The isotope curve and section at St Audrie’s Bay is based on Hesselbo et al. (2002).
observations made by others (Seilacher, 1969, 1984; Obermeier, 1996). The question of whether the seismite records a single or multiple seismic events will be examined later, but the consistent stratigraphic position of the seismite relative to the Westbury Formation, and its consistent scale, intensity and style of soft-sediment deformation across many sites (Fig. 2), suggests that it represents a single event. Hence its lateral extent is significant for assessing the magnitude of the seismic event. Good exposures reveal that typically a metre or more of strata above, and sometimes including, the top of the Westbury Formation are affected by mild to intense deformation (Fig. 3). This ranges from small microfaults through to almost complete liquefaction. Folds, often recumbent and up to several decimetres across, are often the most conspicuous element of the deformation. Surviving borehole material and most published records are generally sufficient only to confirm the presence and approximate position of the seismite within the Penarth Group, though all are consistent with observations made elsewhere at outcrop. Desiccation cracks, a feature accorded some significance by Mayall (1983), cut through the deformed bed at the Bristol Channel sites. However, their sharply defined edges, and the truncation of deformed laminations by the hiatus, indicate that they are not primary features of the seismite and hence, for the purposes of correlation, are of only secondary importance.

Soft-sediment deformation has been observed or reported from more than 40 sites across the outcrop and subcrop of the Penarth Group (Fig. 4). The sites described by Mayall (1983) lie within the Wessex Basin, as broadly defined (Simms et al., 2004). Within this basin soft-sediment deformation has been observed in the lower part of the Cotham Member at numerous sites with a maximum separation of some 120 km and covering an area of >8000 km², from the basin margin setting of south Wales (Figs. 2, 3 middle) (Mayall, 1983; Waters and Lawrence, 1987) and the Mendip Hills (Duffin, 1980) to more basinal settings exposed on the coasts of north Somerset (Whittaker, 1978; Whittaker and Green, 1983) and south Devon (Mayall, 1983) and in the Winterborne Kingston borehole in south Dorset (Ivimey-Cook, 1982).

To the north, in the Severn Basin and on its southern and western margins, soft-sediment deformation in the Cotham Member has been recorded from river cliffs and temporary exposures over a north-south distance of ~75 km, from road construction on the north side of Bristol (Hamilton, 1962), river cliffs at Sedbury, Aust, Westbury-on-Severn and Wainlode Hill (Simms, 2003b), and quarry excavations at Manor Farm, near
Aust Cliff (Figs. 2, 3 Top) (Simms, 2003a). Deformation is commonly conspicuous in secondarily cemented nodules towards the top of the seismite (Fig. 3 Top). Such nodules, developed at this level across the Severn Basin and south-western part of the East Midland Shelf, were long regarded as a single marker band variously termed the *Estheria* Bed, *Naiadita* Bed or *Cypris* Bed (Harris, 1938). Fallen blocks of this ‘bed’ are abundant at the foot of the river cliffs mentioned above though the deformed laminae appear to have long passed unnoticed. In the Stowell Park Borehole, in the north-east of the basin, the only soft-sediment deformation reported is a thin convoluted sandstone bed in the Westbury Formation (Green, 1956). This is the only cored borehole from which substantial deformation has not been recognized at this horizon but observations at well exposed sites indicate that deformation varies both laterally and vertically within sites (Mayall, 1983; Simms, 2003a). Hence clear examples of deformation or sediment liquefaction might be missed or overlooked in the narrow sample represented by a borehole.

The East Midland Shelf, to the north-east of the Severn Basin, forms an extensive platform area extending from the northern flanks of the London–Brabant Massif up to the Market Weighton High north of the Humber estuary. Exposure of the Penarth Group is poor, with the succession known only from temporary excavations and cored boreholes. Nonetheless, soft-sediment deformation has been identified in the lower Lilstock Formation, and sometimes also in the upper part of the underlying Westbury Formation, in every cored borehole (Worssam, 1963; Poole, 1969, 1977, 1978; Horton et al., 1987; Old et al., 1987; Powell et al., 2000) and the few exposures (Kent, 1970; Sykes et al., 1970; Andrew Swift, pers. comm.) of which I am aware. Still further north, in the Cleveland Basin, exposure is poorer still but boreholes in the southern part of the basin (Gaunt et al., 1980) and further north, near Whitby (Raymond, 1955).

Fig. 4. Map showing the locations across the UK at which soft-sediment deformation has been observed or reported from the lower part of the Lilstock Formation of the Penarth Group. Numbers refer to locality details in Appendix A. The orientation of slump fold axes is indicated for those sites for which data are available (data for sites 33–37 from Mayall, 1983).
and Northallerton (Frost, 1998), similarly confirm the presence there of significant soft-sediment deformation in the lower part of the Lilstock Formation.

Beyond the main outcrop belt soft-sediment deformation was recognized at the same level in the Penarth Group in two boreholes in the Cheshire Basin (Poole and Whiteman, 1966), and one in the Carlisle Basin (Ivimey-Cook et al., 1995). Further to the west, the Mochras Borehole in north-west Wales penetrated Upper Triassic rocks beneath an exceptionally thick (>1300 m) Lower Jurassic succession. Soft-sediment deformation was not seen at any level in the Lias Group but was encountered in strata ~18–20 m below the first Psiloceras. This part of the succession differs from typical Penarth Group facies, comprising terrigenous red sandstones, siltstones and mudstones (Harrison, 1971), but palynological evidence (Warrington, 1971) suggests a tentative correlation with the lower part of the Lilstock Formation.

Further afield the discontinuous outcrop of the Penarth Group in Northern Ireland provides few good exposures. Only at two sites on the coast of Co. Antrim, at Larne, ~30 km north–north-east of Belfast, and at Whitehead ~10 km to the south-east of Larne (Simms, 2003b) are fairly complete successions exposed. Soft-sediment deformation is conspicuous in the middle part of the Penarth Group at both sites, and was noted at Larne (Figs. 2, 3c) by Ivimey-Cook (1975). These, and other patchy exposures of the seismite in east Co. Antrim (Griffith and Wilson, 1982; personal observations), all lie within the Larne–Lough Neagh Basin. The Rathlin–Foyle Basin to the north-west is separated from the Larne–Lough Neagh Basin by the Highland Border Ridge. Here too soft-sediment deformation is present at the same level in the Penarth Group of the Magilligan Borehole and from poor surface exposures (Bazley et al., 1999). Magilligan, in north-west Co. Londonderry, represents the most north-westerly outcrop/subcrop of the Penarth Group in the United Kingdom, more than 600 km from the Winterborne Kingston Borehole in south Dorset.

In all, the seismite in the lower part of the Lilstock Formation is found across the entire UK outcrop and subcrop of the Penarth Group, a north–south distance of about 600 km, east–west separation of about 400 km, and total area of at least 250,000 km² (Fig. 4). Nonetheless, its scale of development at even the most widely separated sites, >1 metre thick at Pinhay Bay (N.B. the descriptions in Mayall, 1983, are incorrect; the section at Pinhay Bay is much better exposed than that at Culverhole Point) and nearly 4 metres thick in Northern Ireland (Fig. 2), indicates that it must once have extended far beyond this. Documentation of correlative successions beyond the UK, both offshore and in mainland Europe, is poor and the seismite, if present, has gone unrecognized. Only Mader (1992, p.306) reported similar sedimentary phenomena at this stratigraphic level, noting that “the middle intercalation of the Upper Member of the Rhaetian Formation in the Lodève region of southern France] documents a high-energy event of exceptional and quasi-instantaneous character which... could be attributed to a tsunami...” Although located >1000 km south-east of southern England (Fig. 7), a large tsunami could easily travel such a distance in a matter of hours.

4. Detailed stratigraphy and interpretation of selected sites

Exposures of the Lilstock Formation seismite on the Bristol Channel coasts were described by Mayall (1983) and Hesselbo et al. (2004) but published descriptions from other sites commonly lack detail. Of additional sites identified in 2002 and 2003 only Manor Farm Quarry, near the Severn Bridge north of Bristol in south-west England, and the coastal exposures at Larne and at Whitehead, north-east of Belfast in Northern Ireland, were comparable in their extent and quality of exposure (Fig. 2).

4.1. South-west England

Manor Farm Quarry, excavated in the mid-1990s as a borrow pit for the approach roads to the Second Severn Crossing, exposes a section from a few metres below the Blue Anchor Formation of the Mercia Mudstone Group, through the entire Penarth Group and into the base of the Lias Group (Radley and Carpenter, 1999). The Cotham Member, ~2.5 metres thick, is sharply demarcated from the dark laminated shales of the Westbury Formation beneath. In many places the contact is sheared and deformed, with elongate angular clasts of dark shale incorporated into the basal decimetre or so of the Cotham Member. Deformation pervades ~2 m of the pale grey to brown mudstone and siltstone of the Cotham Member above this contact, although weathering and surface wash obscure many of the deformational features. Recumbent folds and patches of near-structureless sediment caused by liquefaction are ubiquitous. In places irregular, subvertical, ‘ribs’ of pale siltstone suggest upward movement of liquefied silt through the contorted strata. Deformation is particularly conspicuous in secondarily cemented nodules (the so-called ‘Estheria Bed’) that occur towards the top of the seismite (Fig. 3 Top). The deformed beds are truncated sharply by a planar surface...
capped by a conspicuous 2–3 cm thick layer of ferruginous sand. This sand layer, noted also by Richardson (1905) at Sedbury Cliff, 4 km to the north–north-west, is overlain by ~0.5 m of blue-grey silty mudstone with starved ripples but with no evidence of contemporaneous soft-sediment deformation. At the top of the Cotham Member is the famous ‘Cotham Marble’, a discontinuous 0.1–0.2 metre thick stromatolite horizon (Hamilton, 1961; Mayall and Wright, 1981), which is succeeded directly by shelly mudstone and limestone of the Lias Group.

4.2. Northern Ireland

In north-east Ireland the Penarth Group is well exposed only at two sites; at Larne, 30 km north–north-east of Belfast, and at Whitehead 20 km northeast of the city (Fig. 4).

Near Whitehead a faulted outcrop of the Penarth Group is exposed in a small cliff and foreshore at Cloghan Point, on the north side of Belfast Lough. The division between dark laminated mudstones and fine sandstones of the Westbury Formation and paler mudstones and siltstones of the overlying Lilstock Formation is clear. A pale grey sandstone at the top of the Westbury Formation, exposed on the foreshore, shows local minor folding while almost structureless liquefied siltstones, recumbent folds up to 0.7 m across and 0.5 m thick, and abundant syndeformational bedding-plane slickensides, are evident in the reddish-brown, often blocky, mudstones of the Lilstock Formation higher in the succession. About 1.7 m of deformed mudstones are exposed in the cliff with perhaps another 2 m poorly exposed among the boulders on the shore. The deformed beds are overlain by undeformed, grey, coarsely laminated mudstones and siltstones with wave-rippled fine sandstones which pass upwards over ~1 m into mudstones with minor sand flasers.

A clearer and more continuous section is exposed on the foreshore at Larne. Dipping at ~ 20°–30° to the northwest, strata from the Mercia Mudstone Group through to the basal Sinemurian of the Lias Group are exposed, with much of the Penarth Group and Blue Anchor Formation also exposed in degraded cliffs and a small quarry immediately inland (Ivimey-Cook, 1975). The rocks across much of this site, from the foreshore to the top of the cliff more than 15 m above, have been altered to low hornfels grade by Paleocene thermal metamorphism. This has rendered the Penarth Group more resistant to weathering and erosion than correlative strata at Cloghan Point, while many of the sedimentary structures have been highlighted through ‘bleaching’ of the siltstones and sandstones. Consequently this section, probably the thickest and most complete example of the deformed beds anywhere in the UK, is particularly instructive for assessing if the soft-sediment deformation represents one or more than one seismic event.

As elsewhere, dark pyritic shales of the Westbury Formation are succeeded abruptly by paler mudstones and siltstones of the Cotham Member of the Lilstock Formation, here more than 8 m thick. On the smooth, shingle-worn exposure immediately below the promenade several, apparently distinct, sedimentary units showing varying degrees of deformation were recognized within the seismite (Fig. 2) (Fig. 1B in Simms, 2003a). Few of these ‘units’ can be traced laterally for any distance, a phenomenon noted at other sites (Mayall, 1983), and 30 m seaward along strike to the NNE only four are discernable (Fig. 2).

Almost half of the Cotham Member here, approximately 3.9 m in all, is affected by some degree of deformation varying from almost undisturbed or microfaulted laminae through to strata showing almost complete liquefaction and destruction of original sedimentary structures (Fig. 3 Bottom). Decimetre-scale recumbent folding and bedding plane slickensides, the latter with a wide spread of orientations, is particularly conspicuous. Locally, deformation affects the top decimetre or so of the Westbury Formation. Within this pervasive deformation two units appear to be traceable, undisturbed, across much of the outcrop which would seem to suggest that more than one seismic event is represented. The more conspicuous of these, termed the ‘Undeformed Bed’ on Fig. 2, lies about 2.6 to 2.8 m above the Westbury Formation. It is about 0.2 to 0.3 m thick and comprises coarsely laminated mudstone with thin ripple-laminated sandstone layers. However, towards the seaward end of the exposure it pinches out and passes into typical deformed and sheared bedding over a distance of several metres (Fig. 3 Bottom). A little over half a metre higher a thin unit of wave-rippled sandstone and mudstone alternations appears to drape a truncated surface of the contorted strata beneath but, less than 0.1 m higher, passes up into a further half metre or so of intensely deformed strata. Close examination reveals that this apparently undisturbed unit actually undulates gently over the strata beneath, exhibits local minor deformation and microfaulting, and is discontinuous across the exposure. Both the style of deformation and the wide spread of bedding plane slickenside orientations in the seismite both at Larne and at Whitehead indicate foundering of soft sediments during a major seismic event. The somewhat intriguing occurrence within the succession of largely undeformed units appears to be
attributable to more cohesive horizons at which décollement of adjacent strata has occurred.

Approximately the top half metre of the deformed strata at Larne, from about 3.5 to 3.9 m above the base of the Lilstock Formation, is of a different character to the deformed strata below. It contains discrete clasts in which the lamination, again commonly deformed, is discordant to that of the host rock. These clasts, the largest more than a metre across and 0.15 m thick, appear identical to lithologies in the seismite below and show deformation consistent with reworking of consolidated but unlithified sediment. This unit of rip-up clasts is succeeded abruptly by a conspicuous, but discontinuous, pale-bleached, hummocky-cross-laminated sandstone ∼5–6 cm thick, which in turn passes up into a series of pale wave-ripple-laminated sandstones separated by thin darker units (Fig. 5 Top). These rippled sandstones and mudstones extend up to almost 5 m above the base of the Lilstock Formation but, unlike the deformed units below, clearly do represent more than one period of deposition. At about 4.6 m above the base of the Lilstock Formation a 0.15 m thick mudstone dominated unit is penetrated by abundant sandstone-filled desiccation cracks up to 3 cm wide and 0.22 m deep (Fig. 5 Bottom). This is overlain by wave-rippled sandstones, best seen towards the seaward edge of the exposure, and testifies to at least a brief period of emergence and non-deposition.

The rip-up clast breccia and immediately overlying hummocky and ripple-cross-laminated sediments are consistent with erosion and ensuing deposition under turbulent conditions. A tsunami following the seismic event could have produced such facies (Simms, 2003a). The first, and most energetic, waves would have scoured the sea floor while the waning phase, with both primary and reflected waves, could have deposited the rip-up clast breccia and then smaller-scale symmetrical cross-laminated sediments. However, the clear evidence for a hiatus within the succeeding ripple-cross-laminated facies casts some doubt on such an interpretation. Instead it lends support to the interpretation of Hesselbo et al. (2004) that at least the upper part of the Lilstock Formation here, above the hiatus, may represent a storm-dominated siliciclastic shoreface environment. The upper ripple-laminated unit and the desiccated surface beneath at Larne invites comparison with the ripple-laminated facies and desiccation cracks that succeed the seismite unit at exposures in south-west England (Duffin, 1980; Mayall, 1983). If the hiatus at these widely separated localities represents a single synchronous event (Fig. 2) then it implies that, despite their apparent similarity, the ripple-laminated facies below the hiatus at Larne may have had a different origin from that above it.

5. Determining the epicentre and magnitude of the Lilstock Formation seismic event

Spectacular examples of slumping and soft-sediment deformation occur at many levels in the Phanerozoic of the UK and Ireland (e.g. Gill, 1979; Woodcock, 1976).
Although they may affect many metres of strata and extend across hundreds or even thousands of km², nonetheless they appear confined to specific sedimentary basins. Synsedimentary fault movement, a potential trigger for soft-sediment deformation, is well documented throughout the Triassic and Jurassic of the UK yet few such instances have been identified and all appear to be relatively local in extent (e.g. Hallam, 1960; Wignall, 1989; Wignall and Pickering, 1993; Wignall, 2001a). In contrast the soft-sediment deformation seen within the lower part of the Lilstock Formation presents an exceptional pattern. Affecting only a few metres of strata, nonetheless it extends across at least eight sedimentary basins in Britain and Northern Ireland. At no other stratigraphic level is soft-sediment deformation known to affect the entire UK outcrop and subcrop of a sedimentary unit, or even extend beyond the confines of a single sedimentary basin. Discrete earthquakes associated with individual basin-bounding faults might normally be expected to show some stratigraphic spread. Instead the consistent stratigraphic position of a single body of deformed sediment suggests either a seismic event of unique and exceptional magnitude with a single epicentre, or else a mechanism triggering synchronous earthquakes on discrete faults.

In a study of soft-sediment deformation associated with historic earthquakes, Obermeier (1996) established a correlation between earthquake magnitude (M) and the distance from the epicentre to the furthest sediment liquefaction feature. Earthquakes of Magnitude 9 could be detected over distances of almost 500 km, but for Magnitude 8 this was <300 km (Fig. 6). Even without locating the epicentre of the Lilstock Formation seismic event, Obermeier’s results are potentially useful for estimating its magnitude. The potential minimum distance to the furthest observed liquefaction feature in the Lilstock Formation would assume an epicentre located midway between the most widely separated sites. With a radius of ∼300 km this corresponds to an earthquake of Magnitude >8. However, no ‘bulls-eye’ pattern of diminishing thickness of deformation away from such a putative, centrally located, epicentre is evident. Furthermore, the substantial thickness of sediment affected, typically more than a metre and up to nearly 4 m in Northern Ireland, indicates that even sites at the known limit of deformation lie well within its original limits. The fairly consistent scale and intensity of deformation at all of the sites investigated across a 600 km north–south transect of the UK suggests instead that the epicentre was located beyond the envelope of the documented sites. This indicates a distance to epicentre for this event of 400 km to 500 km, possibly even more, implying a Magnitude 9 earthquake or greater.

Locating the epicentre can be attempted using the orientation of deformation features in the Lilstock Formation. Ground motion associated with seismic events is initially directional, with P waves causing longitudinal vibrations in the direction of travel. The motion subsequently becomes chaotic through interference with lateral and vertical motion due to S waves and surface waves (McCall, 2005). Hence sedimentary structures caused by seismic shock might be expected to show some degree of preferred orientation reflecting this sequence of events. Obermeier (1996) actually found that local geological and topographic conditions had a greater influence on the orientation of earthquake-induced dykes than the direction of shaking, though his observations were in terrestrial settings where topography and anisotropy of sediments typically are greater than in marine settings. Pratt (1998) similarly considered that shaking direction was only one of several factors influencing the shape and orientation of synaeresis cracks, which he considered to be caused by earthquakes. In contrast, Terry et al. (2001) observed a much better correlation between the orientation of sediment liquefaction features in Late Cretaceous shallow-marine sediments of South Dakota, USA, and the direction of shock waves emanating from the end-Cretaceous Chicxulub impact site to the south.
In terms of palaeoenvironmental setting, the shallow marine succession studied by Terry et al. (2001) represents a better analogue for the Penarth Group than those described by Obermeier (1996) or Pratt (1998). Mayall (1983) noted a strong preferred orientation of slump fold long axes in the Lilstock Formation seismite in south Wales and north Somerset (Fig. 4) but additional data have been collected only from a further five sites, with only two of these yielding more than 10 measurements. At each site there is a strong preferred orientation of slump fold long axes. These swing around progressively from ENE–WSW in east Devon, through northeast–southwest around the Bristol Channel, to northwest–southeast in Northern Ireland (Fig. 4). Projections drawn at right angles to the slump fold axes at these seven sites converge to the west and intersect at various points in south-west Wales, the Irish Sea and the Irish midlands (Fig. 7). Despite the lack of a single convergence point, the observed pattern may indicate a single epicentre if the views of Obermeier (1996) and Pratt (1998) are also borne in mind. A broad spread of orientations, as might be anticipated if each occurrence was triggered by movement on independent basin-bounding faults, is not evident.

The closest location to a single epicentre in the southern Irish Sea would be the Mochras Borehole (Fig. 4, site 13), ~100 km to the north-east, with the east Devon sites (Fig. 4, sites 39 and 40) ~200 km to the south-east, the Northern Irish sites ~300 km to the north (Fig. 4, sites 1–7), and the most distant sites, in the Cleveland Basin (Fig. 4, sites 9–12), ~400 km to the north-east. An epicentre further to the south or west would increase these distances. These figures, together with the substantial preserved thicknesses at even the more distant sites, suggest that liquefaction effects extended considerably beyond 400 km from the putative epicentre. This would necessitate a minimum earthquake approaching Magnitude 9. Such a conclusion raises significant issues in terms of potential mechanisms that might generate such a powerful seismic event in this region of the globe.

6. Possible causes of the Rhaetian seismite and tsunami

Basic mechanical properties of rocks in the Earth’s crust limit the potential energy that can build up at stress loci before it is released by fracturing of the rock. Even the largest terrestrially generated earthquakes, associated with subduction zones (Nuttli, 1983), seldom exceed Magnitude 9 (e.g. Chile 1960, the largest recorded earthquake, M 9.6; Alaska 1964, M 9.2; Sumatra 2004, M 9.0). However, in late Triassic times, as now, Britain and Ireland lay far from such a tectonic setting. Indeed, throughout the British Phanerozoic there is little evidence for more than local seismic disturbance of sediments even adjacent to some of the largest synsedimentary faults.

Seismic activity associated with volcanism might be invoked as a possible cause of the seismite, particularly as the Triassic–Jurassic boundary interval witnessed the eruption of the Central Atlantic Magmatic Province (CAMP) flood basalts. This possibility was suggested by Hallam and Wignall (2004) but seems unlikely. The seismite lies hundreds of km to the north and northeast of the nearest CAMP volcanic rocks (Fig. 7), necessitating a seismic shock of prodigious magnitude to generate a seismite at such a distance, yet basalt volcanism tends to be effusive rather than explosive (Self et al., 1997). Furthermore, no significant contemporaneous soft-sediment deformation has been reported from locations close to or within the Central Atlantic Magmatic Province.

A third terrestrial mechanism has recently been suggested by Morgan et al. (2004). They invoke mantle plume induced lithospheric gas explosions, or ‘Vernesshot Events’, to account for apparent links between ‘impact signals’, continental flood basalts and mass extinctions at various levels in the Phanerozoic. They cite the Lilstock Formation seismite described here, the CAMP flood basalts, and the Late Triassic extinctions as just one example, but at present the ‘Vernesshot’ hypothesis remains largely speculative.
Although there is an upper limit to terrestrial seismic shocks, much more powerful seismic shocks can be generated by the impact with Earth of a large meteoroid travelling at cosmic velocities (>11.2 km/s) (French, 1998). An impact mechanism has been convincingly invoked for various sedimentary features observed in Cretaceous–Paleogene boundary successions and provides a potentially plausible explanation for the unique extent of the Lilstock Formation seismite.

The seismic effects of the end-Cretaceous Chicxulub impact on contemporaneous sediments are well documented. The Chicxulub impact is estimated to have released more than 200 times the total annual energy output of the Earth (French, 1998), generated an earthquake of ~Magnitude 13 (Covey et al., 1994), and caused ground motion of >1 metre amplitude across some 20% of the Earth’s surface (Boslough et al., 1996). Large-scale submarine failures and gravity flows of end-Cretaceous sediments into deep water up to 2830 km from the Chicxulub Crater (Bralower et al., 1998; Klaus et al., 2000; Norris et al., 2000) testify to the seismic effects of this event. In South Dakota, more than 2700 km north of the impact site, a half- to five-metre thick horizon of slump folds, clastic dykes and homogenized (liquefied) beds in end-Cretaceous shallow marine strata (Terry et al., 2001) perhaps represent a closer analogue to the deformation seen in the Lilstock Formation. At El Mimbral, in northeastern Mexico, more than 1000 km to the west of the Chicxulub impact site, marine sediments of latest Cretaceous strata also show soft-sediment deformation and are succeeded by a 2–3 metre thick succession passing upwards from intraclast breccias, through graded laminated beds, to ripple cross-laminated beds. Smit et al. (1992) attributed this latter sequence to deposition by a tsunami generated by the impact, with supposed tsunami deposits also reported from the Cretaceous–Paleogene boundary interval at other sites (e.g. Bourgeois et al., 1988). Nonetheless, agreement on such an interpretation is by no means unanimous (Stinnesbeck et al., 1993). Whatever the ultimate cause of the seismic event that affected the Lilstock Formation, whether generated by a terrestrial or extraterrestrial mechanism, the observations of Terry et al. (2001), Smit et al. (1992) and Bourgeois et al. (1988) do invite comparison with the observations reported here.

7. An end-Triassic impact?

The unprecedented scale, for the UK, of the Lilstock Formation seismite, and the lack of any obvious tectonic structure with which it might be linked, are significant factors in proposing bolide impact as a possible cause. However, supporting evidence for such a scenario is limited at present. The Manicouagan impact crater, 100 km in diameter and <2000 km from the UK in late Triassic palaeogeographic reconstructions (Fig. 7), might be considered a candidate but for its significantly earlier date of ~214 Ma ago (Hodych and Dunning, 1992) against ~ 200 Ma ago for the Lilstock Formation (Pálfy et al., 2000; Hesselbo et al., 2002). Further, indirect evidence for this age mismatch comes from soft-sediment deformation in the late Triassic (early Norian) Blomidon Formation of Nova Scotia (Fig. 7) (Ackermann et al., 1995; Tanner, 2002), ~700 km to the north of the impact, and an horizon of microtektites and shocked quartz, dated to ~214 Ma ago, within the Mercia Mudstone Group of southern England (Fig. 7) (Walkden et al., 2002). Few other impact craters have ages close to the Triassic–Jurassic boundary interval (Spray et al., 1998) and none approaches Manicouagan in scale. The Puchezh–Katunki Crater in Russia, with a diameter of 80 km, has been suggested as end-Triassic in age but the evidence more strongly favours a Mid-Jurassic age (Pálfy, 2004). Located more than 2500 km north-east of the UK, this crater is too distant to represent a plausible candidate for the epicentre of the Lilstock Formation seismite.

The apparent lack of any obvious candidate impact crater is not necessarily surprising. Although >150 impact craters are now known worldwide (Norton, 2002) this is significantly less than is estimated from the predicted meteorite flux (Chapman and Morrison, 1994). The known record is strongly skewed towards craters formed within the last 50 million years (French, 1998). Older craters are more likely to have been destroyed by erosion and/or concealed beneath younger rocks. Inevitably ~70% of meteorites fall into the sea and hence impact structures there will be still more difficult to detect, even assuming that such craters are not subsequently destroyed by subduction. There is plenty of scope offshore from Britain and Ireland for a hidden crater perhaps 40–50 km in diameter, the product of a ~3 km diameter bolide impact (Marcus et al., 2004). Much of the Triassic in the southern Irish Sea and St George’s Channel lies beneath 2–3 km of younger rock (Naylor and Shannon, 1982) so detection of any concealed impact structure would depend on geophysical investigations or chance interception by a borehole. No obvious candidate structure has yet been identified and geophysical signals of impact structures are seldom clear and unambiguous (French, 1998).

In the last two decades there have been several claims for an end-Triassic bolide impact, based on various lines of evidence from Triassic–Jurassic boundary sections in
widely scattered locations. Shocked quartz was reported from Austria (Badjukov et al., 1987) and Italy (Bice et al., 1992). Subsequent reanalysis was unable to confirm the former (Hallam, 1990) while Bice et al. (1992) conceded that it was impossible in the latter case to establish the precise age of the shocked quartz (at least three separate horizons were recognized), whether the grains were reworked, or even that the planar deformation features they observed were actually due to shock metamorphism. An Iridium anomaly and fern spike was reported by Olsen et al. (2002) in the Newark Basin (Fig. 7), but the anomaly is relatively minor and significant doubts surround its correlation with the marine Triassic–Jurassic interval in Europe (Hounslow et al., 2004). A Platinum Group element anomaly, intermediate between crustal and ordinary chondrite (meteoritic) values, was reported by Fujiki et al. (2003) from thin red and yellow beds within a deep marine sequence of green bedded cherts in Japan. Fullerenes, interpreted as evidence for a carbonaceous chondrite impactor, also were tentatively identified by Perry et al. (2003) in the section at Kennecott Point, Queen Charlotte Islands, British Columbia.

These isolated, and largely unconfirmed, findings fail to lend strong support to hypotheses of an end-Triassic impact and, by implication, an impact cause for the Cotham Member seismite. Further doubt comes from analysis of Osmium and Rhenium isotopes through the Triassic–Jurassic boundary interval at St. Audrie’s Bay. Cohen and Coe (2002) ascribe changes in the isotope ratios of these elements across this interval entirely to igneous activity, and more specifically to the onset of volcanism in the CAMP. Their data largely preclude involvement of an iron or chondritic meteorite of any great size although, since Re and Os abundances are three to four orders of magnitude lower for achondrite meteorites or comets, they concede that such impacts could have occurred without significantly influencing the terrestrial Re and Os signature.

8. Relative timing of Triassic–Jurassic boundary events

The evidence from the Cotham Member on the whole suggests that the seismite was caused by a single seismic event of exceptional magnitude. However, an alternative possibility is that the apparently single event actually represents near synchronous movement on several faults across the UK, triggered by some external event. In the context of asteroid impact, Paine (2004) has suggested that earthquake effects associated with impacts are actually accentuated by premature triggering of incipient terrestrial earthquakes as the impact shock waves travel around and through the Earth. A further possibility is that the C sediments were unusually susceptible to liquefaction by seismic shock. Hence the earthquake that generated the seismite may have been large but not unprecedented for the UK Phanerozoic. Silt and fine sand, such as makes up a significant component of the deformed Cotham Member, are particularly susceptible to liquefaction (Obermeier, 1996) and hence lithology undoubtedly played a significant role in the formation of the seismite. Nonetheless, such lithologies are common throughout the UK Phanerozoic, thereby emphasizing the uniqueness of the Lilstock Formation seismite.

The precise relationships between the seismite, the Initial Isotope Excursion and biotic changes through the Triassic–Jurassic boundary interval, remain unclear. The seismite clearly does represent an extraordinary event that correlates closely with these other two events. But the timing of these events, in particular the seismite/tsunami and the Initial Isotope Excursion, needs to be resolved more closely. Hesselbo et al. (2002, 2004) showed that at St Audrie’s Bay the start of the Initial Isotope Excursion is 0.1–0.3 m above the desiccation cracked erosion surface (Fig. 2) and hence must have occurred some time after this surface was formed. The duration represented by this hiatus is critical to assessing if there was any genuine link between the events. If it represents only a few months or years then a causal link is indicated; if centuries or longer then such a link seems unlikely. The key to resolving this issue lies perhaps in comparable isotope analysis of the exceptionally thick sections in Northern Ireland. At present the precise timing of the two events is not sufficiently resolved to eliminate the possibility that they represent a mere coincidence of otherwise unrelated events.

The precise relationship of these two events, whether related or not, to the biotic changes is more difficult to resolve since the latter is defined largely by negative evidence — the absence of characteristic Triassic taxa. Hence its position may be masked by preservation and/or collection failure. Nonetheless, Ward et al. (2001) and Hesselbo et al. (2002) maintained that there is a good correlation between the isotope excursion and the end-Triassic extinction. The latter authors ascribed the isotope excursion, and by inference the mass extinction, to various effects associated with the onset of CAMP volcanism, with the Rhenium and Osmium isotope data of Cohen and Coe (2002) tending to confirm the timing of this.

With such a convincing correlation between the onset of CAMP volcanism, the isotope excursion and the biotic changes then a potential role, if any, for bolide impact at or very close to the Triassic–Jurassic boundary is
unclear. The seismite certainly suggests an event that is unique in the Phanerozoic history of Britain and Ireland, and that is consistent with bolide impact. However, when the actual energetics of bolide impact are considered, together with possible premature triggering of terrestrial earthquakes, the observed effects could be produced by impact of a relatively modest-sized asteroid, perhaps 3 km across, forming a crater of only 40–50 km diameter. This might also account for the generally rather weak impact signal identified by others at various points around the globe. It has been estimated that impacts on this scale occur with a frequency of 4–5 Ma (Grieve, 1987; French, 1998) and hence are not implicated in any significant extinction events. Even much larger events, such as that which created the 100 km diameter Late Triassic Manicouagan Crater, appear not to have been associated with any significant biotic changes (Walkden et al., 2002). Unless the putative end-Triassic impact was very much larger than the present evidence would seem to allow for, it seems an unlikely primary, or even contributory, cause for the biotic changes across the Triassic–Jurassic boundary.

9. Summary and conclusions

The extraordinary areal extent of soft-sediment deformation in the lower part of the Cotham Member suggests an exceptional cause. The most parsimonious interpretation is for a major seismic event triggering \textit{in situ} foundering of poorly consolidated sediments, but its exact cause remains enigmatic. The seismite may represent separate earthquakes affecting individual basins, only appearing to represent a single event as a consequence of the limits of stratigraphic resolution and correlation between basins. However, its consistent position in the lower part of the Cotham Member, the lack of any evidence for more than one deformational event even at its thickest development, and the absence of similarly widespread phenomena in contiguous parts of the geological column, do not favour such a multiple-event scenario. Preferred orientations of slump-fold long axes from different sites are somewhat equivocal with regard to identifying a single epicentre. Although not showing the wide scatter that might be expected from independent earthquakes, the data also lack the tight focus that might arise from a single epicentre. The pattern observed may instead reflect the interaction of seismic shock waves with local geological and sedimentological anisotropies, or the triggering of more localized earthquakes by an impact generated shock wave.

Assuming that the seismite represents a single event then this raises several possibilities for its cause and magnitude. Volcanism, as suggested by Hallam and Wignall (2004), seems an unlikely cause. The distance between the seismite and any CAMP volcanics, and the nature of flood basalt volcanism (Self et al., 1997), renders any direct link improbable. Similarly, Britain’s tectonic situation in the late Triassic, when the region lay far from any subduction margins, was not conducive to earthquakes of the magnitude implied by the extent of the seismite. On the evidence of its exceptional extent alone, the impact of a 2–3 km diameter asteroid offers an attractive alternative explanation for such a powerful seismic shock. An asteroid or comet of this size can release more seismic energy on impact than even the largest terrestrially generated earthquake. However, no impact crater of the right age has yet been located and other evidence in support of a bolide impact remains inconclusive. The work of Cohen and Coe (2002) even suggests that a major impact was unlikely at this time. The impact of a km-scale asteroid does provide a plausible explanation for the observed sedimentological effects in the Cotham Member across the UK, but the evidence is far from unequivocal. Even if ultimately confirmed as the cause, current evidence does not indicate it as a significant contributory factor in the generation of either the isotope excursion or the biotic changes through the Triassic–Jurassic boundary interval.

Hesselbo et al. (2002, 2004) suggested that the Triassic–Jurassic boundary might be defined by the Initial Isotope Excursion. Such an idea has some merit since the Isotope Excursion represents an apparently synchronous, global, abiotic event rather than being based on species migration after the extinction event. Regardless of whether or not the seismite is directly linked to the isotope excursion and/or biotic changes, its stratigraphic position so close to the Initial Isotope Excursion makes it an exceedingly useful marker horizon. The putative tsunamiite described by Mader (1992) perhaps hints at evidence for this event in mainland Europe and the possibility of correlation beyond the UK.

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Appendix A. Site details

Numbers on Fig. 1 refer to locations from which soft-sediment deformation has been recorded in the Cotham Member (or equivalent) of the Lilstock Formation. Grid references are those of the Ordnance Survey (the national mapping agency of Great Britain) and the Ordnance Survey of Northern Ireland:

Rathlin Trough
2 = The Lynn, Lisnagrib, Northern Ireland [C 709278] — Bazley et al., 1997.

Larne–Lough Neagh Basin
3 = Waterloo Bay, Larne, Northern Ireland [D 409034] — Ivimey-Cook, 1975; Simms, 2003a [overlain by facies interpreted as tsunamiite].
7 = Cloghan Point, Whitehead, Northern Ireland [J 470907] — Simms, 2003a,b.

Carlisle Basin
8 = British Gypsum Ltd Borehole SB1, Carlisle [NY 3114353267] — Ivimey-Cook et al., 1995.

Cleveland Basin
9 = Eskdale No. 8 Borehole, 10 km west-south-west of Whitby [grid reference not cited] — Raymond, 1955 [refers also to deformation of sandstones within the Westbury Formation].

Cardigan Bay Basin
13 = Mochras Borehole [SH 55332594] — Harrison, 1971 [soft-sediment deformation was reported from here in latest Triassic strata which have been correlated, on palynological evidence (Warrington, 1971), with the Penarth Group but are of a facies distinct from typical Penarth Group elsewhere in the United Kingdom].

Cheshire Basin

East Midlands Shelf
16 = Bantycock Quarry, Newark Upon Trent [SK 813495] — Andrew Swift, pers. comm.
20 = Warwick area (locations unspecified) — Old et al., 1987 [refers also to deformation towards top of Westbury Formation in Home Farm Borehole].

Severn Basin

Mendip-South Wales Massif
30 = Sedbury Cliff, Chepstow [ST 557932] — Simms, 2003a,b.
31 = Manor Farm Quarry and Aust Cliff [ST 573897] — Simms, 2003a,b.

Wessex Basin
36 = Doniford Bay [ST 08274345] — Whittaker and Green, 1983.
37 = Lilstock [ST 178454] — Warrington and Ivimey Cook, 1995; Whittaker and Green, 1983.
39 = Culverhole Point [SY 894273] — Mayall, 1983 (N.B. The section at Culverhole Point is very poorly exposed in landslipped blocks. Mayall’s description
probably refers instead to the better exposed section on the shore at Pinhay Bay).


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