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Uniquely extensive seismite from the latest Triassic of the United Kingdom: Evidence for bolide impact?

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ABSTRACT

A 2–4 m thick seismite, in places overlain by a previously unreported tsunamite, can be traced across $>250{,}000$ km^2 of the outcrop and subcrop of the latest Triassic (Rhaetian) Cotham Member of the Penarth Group, United Kingdom, an extent unique for the British Phanerozoic. Its consistent thickness, intensity of deformation, and preferred orientations of slump-fold axes indicate a seismic event of $M > 10$ with an epicenter >600 km W or NW of central Britain. The magnitude of the event is incompatible with known terrestrial mechanisms (fault, volcano) but is consistent with a major bolide impact. A short, but unknown, interval separates the top of the Cotham Member seismite from major geochemical and biotic perturbations associated with the end-Triassic extinction, although a direct link between the seismite and these other events remains equivocal. The exceptional extent of ''mega-seismites'' such as this may prove a useful indicator of previously undocumented bolide impacts.

Keywords: Rhaetian, Triassic-Jurassic boundary, soft-sediment deformation, seismite, tsunamite.

INTRODUCTION

Soft-sediment deformation is a common feature of many sedimentary successions. Although the deformation may be spectacular, with individual slump sheets sometimes many meters thick, their areal extent is limited; even the most widespread examples rarely extend beyond individual sedimentary basins. In many instances, extensive horizons with evidence of soft-sediment deformation can be interpreted as ''seismites,'' linked to known growth faults active during deposition. Confinement of these horizons, in most instances, to individual basins reflects the fact that even the largest terrestrially generated earthquakes ($M > 9$) have a radial distance between epicenter and the furthest liquefaction feature of <500 km (Obermeier, 1996). However, the instantaneous energy release of a large bolide impact can exceed that of the largest earthquake (Nuttli, 1983) or volcanic explosion (S. Sparks, 2002, personal commun.), and hence impact-induced seismic events may affect correspondingly larger areas. For instance, Boslough et al. (1996) estimated that the Cretaceous-Tertiary impact generated a magnitude 13 earthquake, easily sufficient to disturb unconsolidated sediment over a radius of several thousand kilometers. Seismically disturbed end-Cretaceous sediments are known >2800 km from the Chicxulub impact site (Norris et al., 2000; Terry et al., 2001).

Within the British Phanerozoic there is one horizon of soft-sediment deformation in the latest Triassic (Rhaetian), shallow marginal marine to freshwater Penarth Group that is unique in affecting the entire United Kingdom outcrop and subcrop of the Cotham Member (lower Lilstock Formation) (Figs. 1 and 2); no other British example approaches this in areal extent. Reexamination of published sections and boreholes, and identification of new sites[1], reveals that diagnostic features of seismites (Obermeier, 1996) are ubiquitous and pervasive at this stratigraphic level. Although briefly noted at many sites over nearly half a century, and described in greater detail at three sites by Mayall (1983), the scale of development and unique lateral extent—established for the first time here—and the stratigraphic position have implications not considered previously.

PENARTH GROUP (RHAETIAN) SEISMITE

New observations at Larne, in Northern Ireland (Fig. 1, A and B; site Ln in Fig. 2), reveal 3.8 m of intensely deformed mudstone to fine sandstone resting on the deformed and locally sheared top of dark laminated marine mudstones and thin sandstones of the Westbury Formation. Features typical of seismites include decimeter-scale recumbent folds with strong preferred orientation, microfaults, bedding plane slickensides and structureless siltstones. Deformed beds may pass laterally or vertically into undeformed strata, with mudstone-dominated beds less deformed than siltstones or sandstones. Deformation generally is more intense in the lower part of the seismite. The top of the seismite is erosionally truncated and locally brecciated. Above is ~0.2 m of hummocky cross-stratified sandstone succeeded by >1 m of thinly interbedded siltstone and wave-rippled fine sandstone (Fig. 1, A and B) in which soft-sediment deformation is minor and localized. At Manor Farm Quarry (Fig. 1D; site M in Fig. 2), >400 km SSE of Larne, ~2 m of the Cotham Member is similarly deformed, again with vertical and lateral variation in deformation intensity. Recumbent folding and contorted bedding, with strong preferred orientation, is conspicuous in an ~0.2-m-thick carbonate-cemented bed near the top of the member. Deformation is even more intense lower in the section, with extensive evidence of sediment liquefaction including diffuse siltstone dikes. The Westbury Formation mudstones beneath are in places deformed and sheared to a depth of several decimeters. The seismite is erosionally truncated, overlain by 2–3 cm of ferruginous sand and 0.35 m of gray-green mudstone with siltstone-sandstone lenses, and capped by a stromatolite horizon. Exposures in the Bristol Channel (Mayall, 1983) display a similar assemblage including slump folds, minor buckling, and, in less deformed strata, microfaults and fluid-escape structures. The seismite unit, ~1 m thick extending down into the sheared and deformed top of the Westbury Formation, is erosionally truncated and

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[1] GSA Data Repository item 2003078 localities and lithostratigraphy of a late Triassic seismite in the United Kingdom, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

Geology; June 2003; v. 31; no. 6; p. 557–560; 3 figures; Data Repository item 2003078.

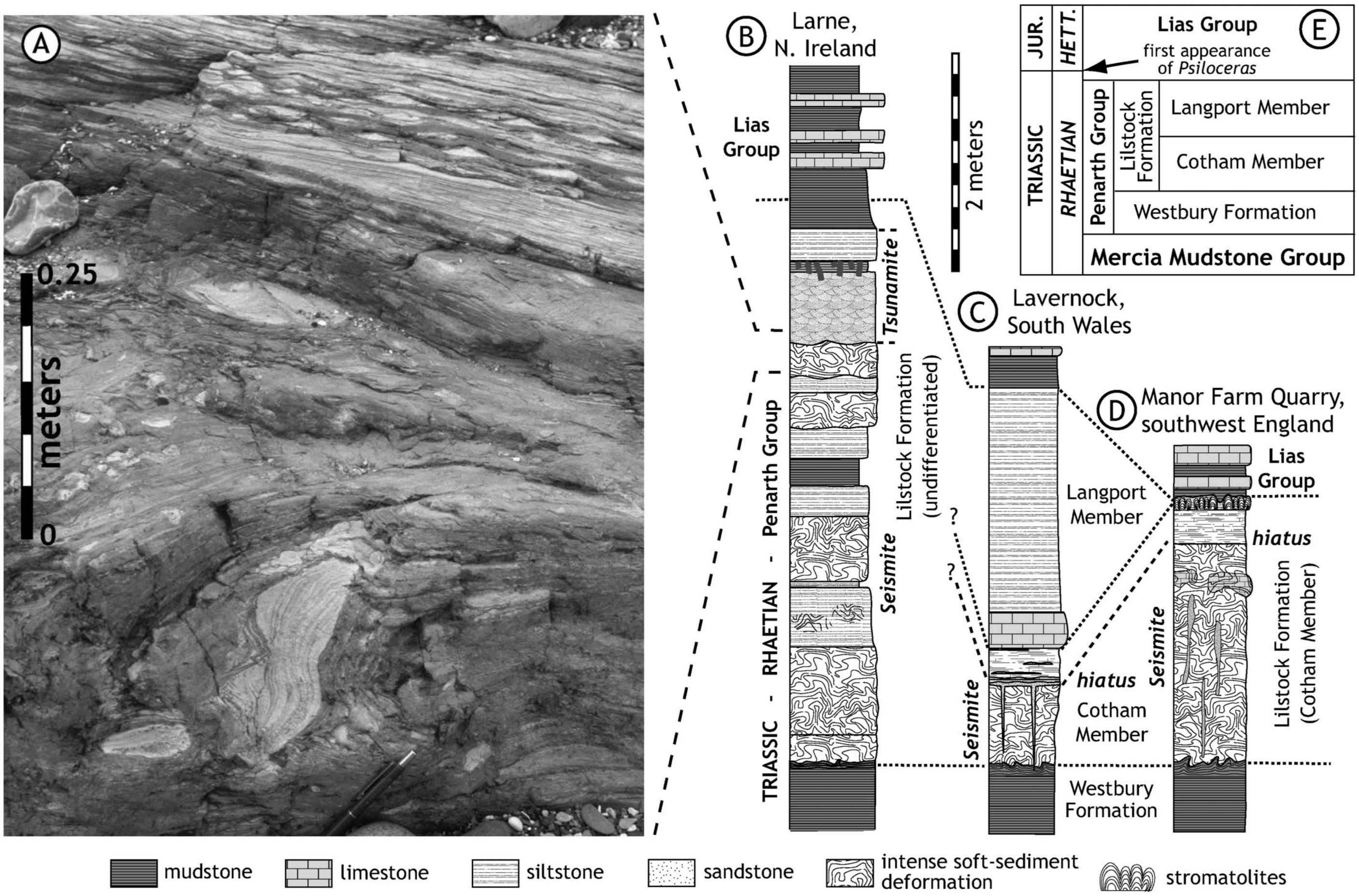

Figure 1. Penarth Group seismite and tsunamite. A: Intensely deformed and brecciated siltstones and sandstones in upper part of seismite unit, erosionally truncated and overlain by hummocky cross-stratified and wave-rippled sandstones at base of tsunamite unit, Larne, Northern Ireland. B–D: Measured sections at Larne, Lavernock, and Manor Farm Quarry (localities Ln, Lv, and M in Fig. 2). E: Litho- and chronostratigraphy of named units across Triassic-Jurassic boundary in United Kingdom. Jur.—Jurassic; Hett.—Hettangian.

overlain by as much as 1 m of thinly interbedded mudstones and wave-rippled sandstones (Fig. 1C). Subvertical clastic dikes up to 8 cm thick form a polygonal network extending down >0.8 m into the underlying seismite from beneath the lowest wave-rippled sandstone bed. More sharply defined than the siltstone dikes at Manor Farm Quarry, they are best interpreted as desiccation cracks (Mayall, 1983) and imply emergence and a minor hiatus after the seismic event.

The extraordinary areal extent of this seismite is consistent with disturbance by a powerful seismic shock. Shearing of the consolidated Westbury Formation mudstones supports this interpretation rather than sediment loading or dewatering in the Cotham Member. At Larne the erosion surface and brecciation at the top of the seismite, and the succeeding hummocky cross-stratified and wave-rippled sandstones (Fig. 1, A and B), are consistent with a tsunami reworking the top of the seismite following the seismic event (Bourgeois et al., 1988). This tsunamite has not been reported previously, although in southern Britain both the tsunamite and top of the seismite are absent, truncated by an erosional hiatus of unknown duration (Fig. 1, C and D).

GEOGRAPHIC AND STRATIGRAPHIC DISTRIBUTION

The Cotham Member seismite has been reported, or observed for the first time, at more than 30 locations (Fig. 2 and Fig. DR1—see footnote one) across >250,000 km^2 of the United Kingdom; I have yet to visit a site at which a substantial seismite is not developed in the Cotham Member. Its thickness is broadly similar across this entire area, though commonly underestimated in the field where diagnostic features may be overlooked in weathered sections. It is 1–2 m thick in southern Britain, where it is truncated by an erosional hiatus, but almost 4 m thick in the apparently complete succession in Northern Ireland (Fig. 1B). In boreholes soft-sediment deformation may occur sporadically (analogous to vertical and lateral variation in surface exposures) through typically 2–4 m of the upper Penarth Group. However, existing borehole logs do not allow the stratigraphic limits of the seismite to be defined, and much of the original borehole material has been destroyed. The seismite's considerable thickness at even the most widely separated sites indicates that originally it extended far beyond the present known limits. Few detailed descriptions of Rhaetian strata have been published elsewhere in western Europe, although Mader (1992) described a half-meter unit of chaotically disturbed sediments with allochthonous clasts in the Upper Rhaetian of the Lodève region, southern France (Fig. 3). He interpreted this unit as a tsunamite, an interpretation which invites comparison with the Cotham Member seismite and tsunamite in the United Kingdom.

Consolidated mudstones were less susceptible to deformation than the siltstones and fine-grained sandstones that dominate the Cotham Member, in a manner analogous to observations by Obermeier (1996). Although deformation of thin sandstones within the Westbury Formation mudstones has been observed at Larne and other sites (Fig. DR2—see footnote one), seismite thickness may partly reflect the depth of susceptible sediment (silts and sands of the Cotham Member) at the moment of the seismic event. Seismites, by their very nature, affect pre-existing strata; hence the seismic event must immediately post-date the youngest deformed strata. At Larne this is encompassed by the minor hiatus between the seismite and succeeding tsunamite, while in

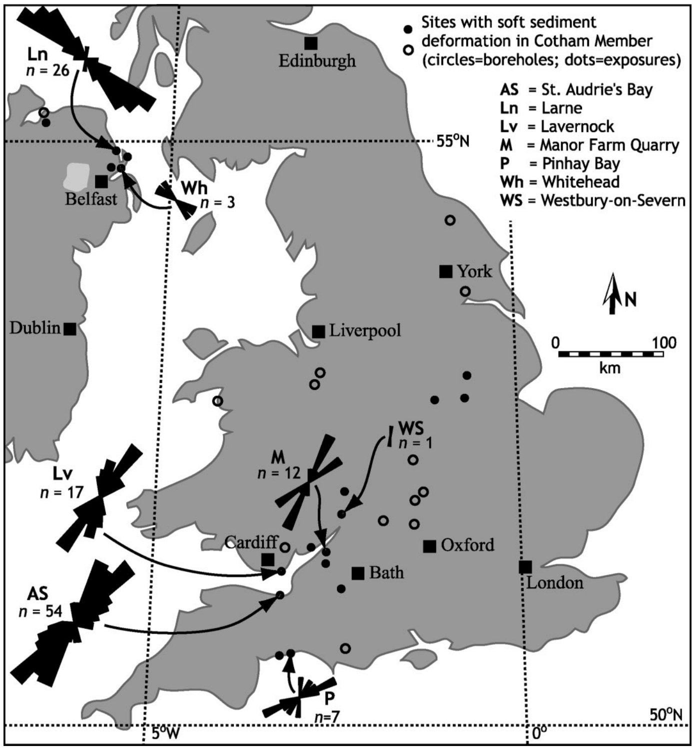

Figure 2. Location of sites in United Kingdom at which soft-sediment deformation is pervasive in Cotham Member of Penarth Group (Rhaetian). Rose diagrams indicate orientation of slump fold axes. For further details of localities see Figure DR1 (see footnote one).

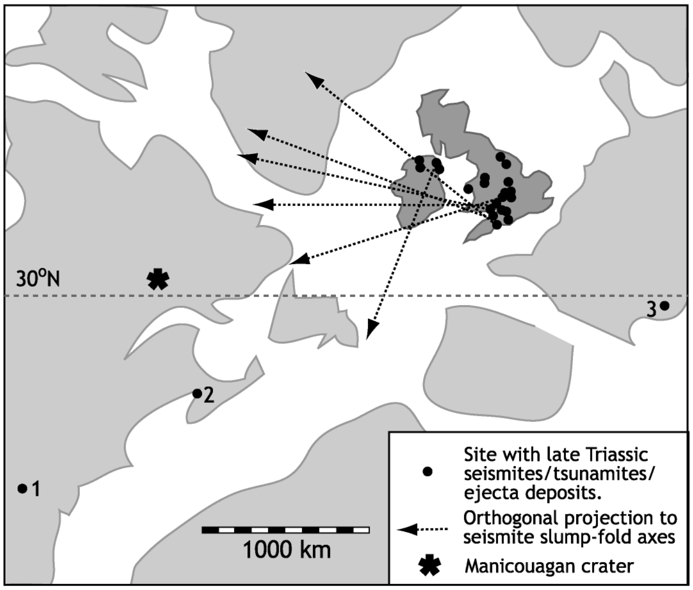

Figure 3. Late Triassic paleogeography of the North Atlantic region (Smith et al., 1981) showing distribution of Cotham Member seismite in United Kingdom and orthogonal projections to slump-fold axes within it. Location of Manicouagan crater and other sites mentioned in text are indicated; 1—Olsen et al., 2002; 2—Tanner, 2002; 3—Mader, 1992. Details of United Kingdom sites are on Figures 2 and DR1 (see footnote one).

southern Britain there is a more substantial hiatus of unknown duration (Fig. 1, C and D). The first appearance of the ammonite *Psiloceras*, currently taken to define the base of the Jurassic in marine sections (Hodges, 1994), typically occurs only a few meters above the seismite (12.6 m at Larne; 7.4 m at Lavernock; 8.8 m at St. Audrie's Bay; ~1.5 m at Manor Farm). The base of the Jurassic has been dated to ca. 200 Ma (Pálfy et al., 2000); the Cotham Member seismic event was probably less than one million years earlier (Hesselbo et al., 2002).

EPICENTER AND MAGNITUDE OF THE SEISMIC EVENT

The deformation intensity of the Cotham Member seismite is consistent across the entire United Kingdom, while thickness varies by a factor of less than three even without taking into consideration the proven hiatus at southern sites. These observations suggest that the epicenter may have been located at a distance from central Britain greater than the maximum separation between sites (~600 km), and certainly beyond the present limit of the United Kingdom outcrop and subcrop. From Obermeier's (1996) work the distance from central Britain to the epicenter suggested here (>600 km), and the scale and intensity of deformation across >250,000 km^2, indicate a seismic shock significantly greater than magnitude 9.

The preserved extent, >250,000 km^2, of the Cotham Member seismite is more than an order of magnitude greater than any other known in Britain or Ireland, yet this is only a fraction of the original total area affected. Synsedimentary fault movement, one possible cause, is well documented in the British Mesozoic (e.g., Jenkyns and Senior, 1991), but evidence for significant associated soft-sediment deformation is surprisingly scarce and invariably confined to individual sedimentary basins. Similarly, synsedimentary fault movement is well documented in the Newark Supergroup of eastern North America (e.g., Olsen and Schlische, 1990), although the only major seismite documented appears to correlate with the Manicouagan impact (Tanner, 2002). Volcanism associated with the Central Atlantic Magmatic Province (Hesselbo et al., 2002) might also be invoked as a cause, yet no seismites are reported from this stratigraphic level in the Newark Supergroup, where Central Atlantic Magmatic Province volcanics are well represented, while the United Kingdom lay well beyond the limits of the Central Atlantic Magmatic Province and hence associated seismic effects would be unexpected here. Lithospheric properties actually suggest that normal seismic activity, associated with fault movement or volcanism, is improbable as a mechanism for generating a seismite on this scale. Even were it possible, the question remains as to why this event was of such vastly greater magnitude than any other known in the United Kingdom Phanerozoic, raising the possibility that it was generated by a major bolide impact. Putative impact-induced seismites have been linked to two of the largest known impact structures and occur at considerable distances from them. Terry et al. (2001) described a seismite up to 5 m thick affecting end-Cretaceous strata at sites >2500 km NNW of Chicxulub, while Tanner (2002) has linked a >10-m-thick seismite in the late Triassic of Nova Scotia with the 100-km-diameter Manicouagan crater <750 km to the NNW (Fig. 3). Both of these impacts have been correlated with distal ejecta deposits (e.g., Norris et al., 2000; Terry et al., 2001; Walkden et al., 2002). Another possible impact seismite has been described from the Jurassic of Utah (Alvarez et al., 1998), although this interpretation remains contentious (Bridges, 1999). The rarity of large impact events renders it likely that very few would occur during the Phanerozoic sufficiently close to the United Kingdom to generate a seismite on this scale. Hence, in terms of both magnitude and ultimate cause, a seismic event triggered by a major bolide impact could be unique in the British Phanerozoic. The geographic scale of the Cotham Member seismite tends to support such a scenario although confirmatory evidence, in the form of ejecta deposits, have yet to be identified.

Slump fold axes at 7 sites across the United Kingdom show strong preferred orientations (Fig. 2), which are interpreted to be due to intense lateral shaking of flat-lying sediments by seismic waves and hence are normal to their direction of travel. They are analogous to those reported by Terry et al. (2001) for the end-Cretaceous impact seismite. Orthogonal projections to modal orientations (Fig. 3) intersect in south Wales and southern Ireland, but such putative epicenters are inconsistent with the observed extent and scale of the seismite across the United Kingdom. Overall the data suggest an epicenter somewhere offshore to the west of Ireland. Local variations in slumping direction may reflect seafloor topography (Mayall, 1983) or the effects of secondary seismic excitation of nearby faults (Tanner, 2002); close proximity of the NNW-SSE Larne Lough and Ballytober faults may account for the seemingly anomalous fold-axis orientations at the sites in Northern Ireland.

RELATIONSHIP TO OTHER END-TRIASSIC EVENTS

The giant Manicouagan crater (Fig. 3) significantly pre-dates the seismite described here (Walkden et al., 2002) and no major end-Triassic impact site consistent with these observations has yet been identified, although there is ample scope for a location offshore concealed by post-Triassic cover. The end-Triassic witnessed a major mass extinction for which both bolide impact, tentatively supported by an iridium anomaly and fern spike in the Newark Supergroup (Olsen et al., 2002), and volcanism in the Central Atlantic Magmatic Province (Hesselbo et al., 2002) have been invoked as possible causes. Carbon isotope data across the marine Triassic-Jurassic boundary show an excursion similar to that at the Cretaceous-Tertiary boundary, the initial peak of which has been correlated with the end-Triassic extinction (Ward et al., 2001; Hesselbo et al., 2002). In the United Kingdom this lies within the Cotham Member, >8 m below the first *Psiloceras* occurrence but only 0.3 m above the top of the seismite at St. Audrie's Bay (Fig. 2) (Hesselbo et al., 2002). Although the first *Psiloceras* currently defines the base of the Jurassic (Hodges, 1994), it actually is part of the postextinction recovery fauna; hence both the isotope excursion and the seismite occur at stratigraphic levels appropriate for the extinction event itself. However, inference of a direct link between the seismic event and the mass extinction is weakened by the presence of a hiatus immediately above the seismite at St. Audrie's Bay and elsewhere in southern Britain.

CONCLUSIONS

The Cotham Member seismite is uniquely extensive ($>250{,}000$ km^2) for the United Kingdom, indicating a seismic event more powerful than might be anticipated from known terrestrial mechanisms (fault or volcano) but consistent with a major bolide impact >600 km to the west of central Britain. Chapman and Morrison (1994) estimated that an $\sim$5-km-diameter bolide impacts Earth on average every 6 m.y., but many impact structures must still await discovery. The potentially vast lateral extent of the associated impact seismites can serve as indicators for otherwise hidden impact structures, as may be the case for the example described here.

Although the Cotham Member seismite appears to correlate closely with the end-Triassic mass extinction, the evidence amassed at present is too weak for bolide impact to be implicated unequivocally as the primary cause of the extinction. Indeed, there is mounting evidence that even some of the largest documented bolide impacts may have had little effect on global biodiversity (Walkden et al., 2002). Nonetheless, the ultimate cause of the Cotham Member seismite should be considered a potentially significant factor contributing to the biotic and geochemical perturbations observed only a little above it and hence may play a significant future role in refining the chronostratigraphy of the Triassic-Jurassic boundary.

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