Intense and widespread seismicity during the end-Triassic mass extinction due to emplacement of a large igneous province

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ABSTRACT

Multiple levels of earthquake-induced soft-sediment deformations (seismites) are concentrated in the end-Triassic mass extinction interval across Europe. The repetitive nature of the seismites rules out an origin by an extraterrestrial impact. Instead, this intense seismic activity is linked to the formation of the Central Atlantic magmatic province (CAMP). By the earliest Jurassic the seismic activity had ceased, while extrusive volcanism still continued and biotic recovery was on its way. This suggests that magmatic intrusions into sedimentary strata during early stages of CAMP formation caused emission of gases (SO_2, halocarbons, polycyclic aromatic hydrocarbons) that may have played a major part in the biotic crisis.

INTRODUCTION

The strong temporal link between the end-Triassic mass extinction (ETE; 201.6 Ma) and the oldest dated volcanics of the Central Atlantic magmatic province (CAMP) suggests causality between this large igneous province and the biotic crisis (Blackburn et al., 2013). The ETE has been explained by global warming and ocean acidification caused by volcanic CO_2 and/or methane release as reflected in carbon isotope records across the Triassic-Jurassic boundary (TJB) (Hesselbo et al., 2002; Ruhl et al., 2011). In the United Kingdom the ETE interval exhibits conspicuous deformed sediments with an areal extent of 250,000 km^2 (Simms, 2007) (Fig. 1). At St. Audrie's Bay (United Kingdom) the deformed interval encompasses 1 m of the topmost Westbury Formation and the lower Cotham Member (Lilstock Formation), with its top ~0.3 m below the initial negative carbon isotope excursion (CIE) and 7 m below the first index ammonite (*Psiloceras*) of the Jurassic (Simms, 2007). At Larne (Northern Ireland), the deformed strata consist of four beds partly separated by undeformed beds (Simms, 2007). Simms (2003, 2007) attributed the United Kingdom seismites to a single event triggered by an extraterrestrial bolide impact, although an impact crater of suitable size and age was lacking. Hallam and Wignall (2004) and Wignall and Bond (2008) instead suggested prolonged earthquake activity linked to the CAMP as a cause for the United Kingdom seismites. Improved $^{40}Ar/^{39}Ar$ dating of the small, French Rochechouart impact structure to 201 ± 2 Ma refocused interest on an impact at the TJB (Schmieder et al., 2010; Fig. 1). With an estimated impact energy equivalent to an earthquake of 10.8–10.9 magnitude on the Richter scale (ML), the Rochechouart bolide was a possible trigger of the United Kingdom seismite (Schmieder et al., 2010).

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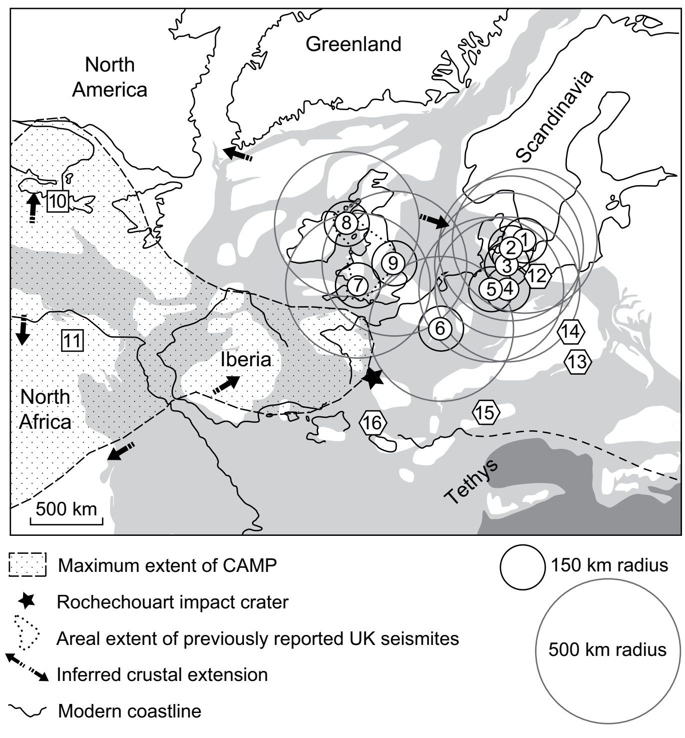

Figure 1. Paleogeographic map of western Europe (after Blakey, 2014), with main investigated seismite localities, extent of United Kingdom (UK) seismites (Simms, 2007), northern extent of Central Atlantic magmatic province (CAMP), and other localities mentioned in text. Circles (150 km and 500 km radius) show hypothetical distance to seismic epicenters from each seismite locality. Star shows location of Rochechouart crater (Schmieder et al., 2010). Arrows show inferred crustal extension (Ruiz-Martínez et al., 2012). Seismite localities (in circles): 1—N Albert quarry, Sweden; 2—Stenlille wells, Denmark; 3—Rødby, Denmark; 4—Mariental, Germany; 5—Schandelah, Germany; 6—Grouft well and Junglinster Heedhaff, Luxembourg; 7—St. Audrie's Bay, United Kingdom; 8—Larne, Northern Ireland, United Kingdom; 9—boreholes near York, United Kingdom. CAMP localities (in squares): 10—Fundy Basin, Nova Scotia; 11—Argana Basin, Morocco. Other localities with disturbed Triassic-Jurassic boundary strata (in hexagons; see the Data Repository [see footnote 1]): 12—Kamień Pomorski IG-1 well, Poland; 13—Csővár section, Hungary; 14—Furkaska section, Slovakia; 15—Val Adrara, Italy; 16—Lovède Basin, France.

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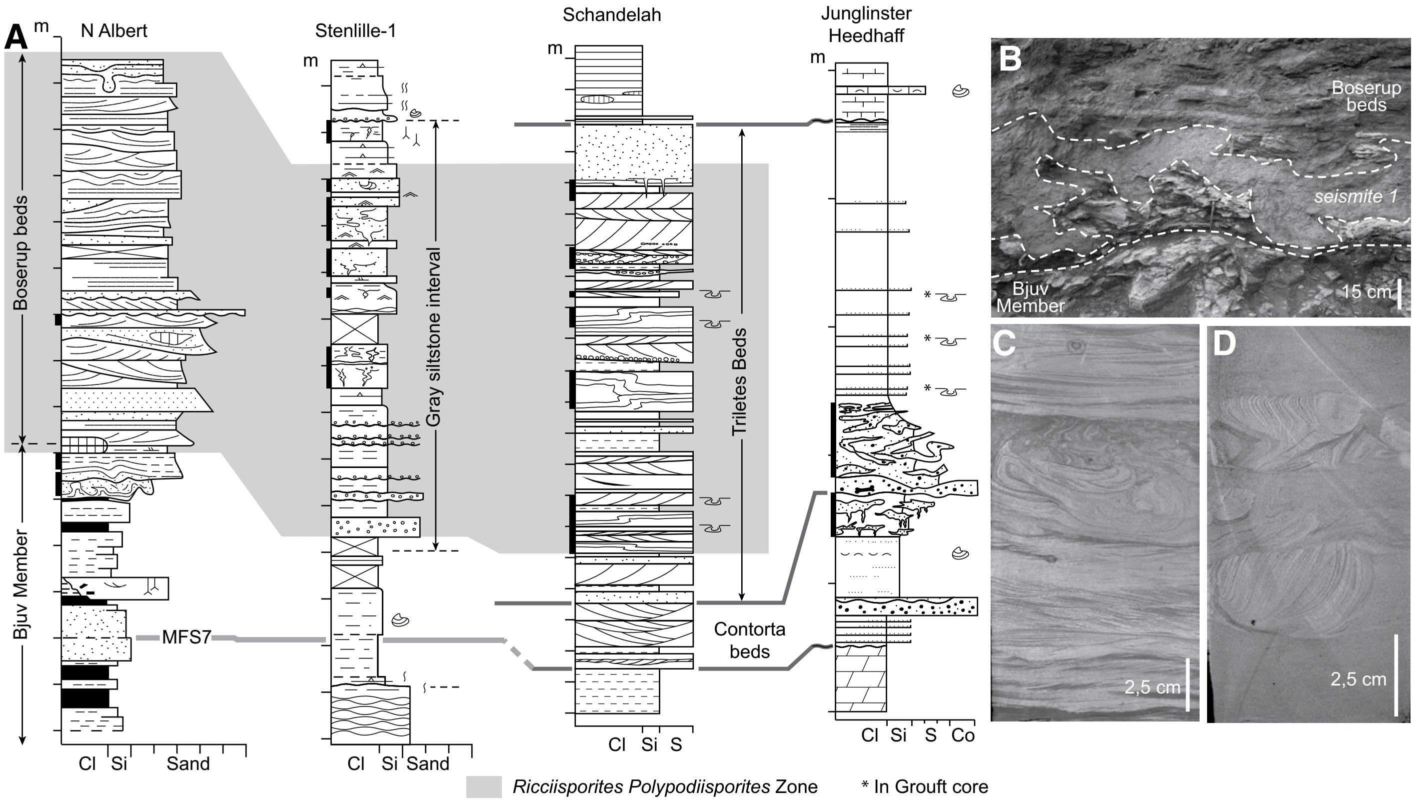

Figure 2. A: Correlation of sedimentary logs from Norra Albert quarry (Sweden), Stenlille-1 well (Denmark), Schandelah well (Germany), and Junglinster Heedhaff (Luxembourg) (expanded version is available as Fig. DR3 [see footnote 1]). Vertical black bars mark seismite levels. Gray field is *Ricciisporites–Polypodiisporites* (RP) Zone. MFS—maximum flooding surface; Cl—clay; Si—silt; S—sand; Co—conglomerate. B: Close-up of seismite 1 in N Albert quarry. C: Soft-sediment deformation structures, attributed to liquefaction, in very fine-grained sandstone. Wave-rippled sandstone below (higher porosity and permeability) was not liquefied, and the one above post-dates the deformation (Stenlille-4 well, 1503.72–1503.95 m). D: Deformed cross-laminated fine-grained sandstone in homogeneous, liquefied, very fine-grained sandstone (Stenlille-1 well, 1496.36–1496.48 m). Additional soft-sediment structures are shown in Figure DR4. Depth and height tick marks on left side of each log represent 1 m.

We examined marine and terrestrial TJB strata from the Danish, German, and Paris Basins (Fig. 1) for sedimentological evidence of seismic shock. At the TJB, these basins constituted shallow, low-gradient embayments on the northern margin of the epicontinental sea that covered large parts of northwest Europe (Nielsen, 2003) (Fig. 1). The sites represent various depositional settings: terrestrial (Norra [N] Albert quarry, Sweden), shallow marine (the Stenlille core, Danish Basin), marine (the Rødby-1, Schandelah, and Mariental cores, German Basin), and condensed shallow marine environments (Junglinster Heedhaff and the Grouft core, Paris Basin) (Fig. 2).The TJB successions at these sites are well constrained by palyno- and chemo-stratigraphy (van de Schootbrugge et al., 2009; Lindström et al., 2012), allowing robust long-distance correlations.

METHODS

The sites were logged and sampled in detail, with interpretations of depositional environments supported by detailed studies of palynology, coal petrology, and stable isotope geochemistry (Fig. 2; see also Appendix DR1 and Figs. DR1–DR4 in the GSA Data Repository[1]). Samples were processed according to standard palynological methods, and ≤300 palynomorphs were counted per slide with a compound microscope at 650× magnification. For the $\delta^{13}C$ isotope analysis of bulk organic carbon, the sediment samples were treated with HCl, rinsed, dried, and ground to a homogeneous powder using an agate mortar. The samples (and U.S. Geological Survey 24 standard) were analyzed using a Flash Elemental Analyzer 1112 (Thermoquest) connected to the continuous flow inlet system of a MAT gas source mass spectrometer (Thermoquest), and by elemental analysis–isotope ratio mass spectrometry. Platinum group element abundances were measured for twenty samples from the N Albert section by neutron activation analysis (NAA). The results are presented in Table DR1 in the Data Repository. Six thin sections from seismites 1 and 2 in the N Albert quarry were examined for shock metamorphic features using a Leitz five-axis universal stage mounted on an optical microscope.

RESULTS AND DISCUSSION

In the terrestrial upper Rhaetian succession at the N Albert quarry (Fig. 1), three levels of soft-sediment deformation are interpreted as seismites (Fig. 2). Seismite 1, a strongly deformed 0.2–0.3-m-thick, fine-grained sandstone bed in the uppermost part of the clay- and coal-dominated Bjuv Member (Höganäs Formation), is present throughout the quarry. It exhibits intense folding, ball-and-pillow structures, and irregular flame structures (Figs. 2A and 2B). Underlying sediments are deformed only in close proximity to seismite 1, and fluidization structures or sand injections into the overlying coarser beds (seismite 2; 0.5 m thick) are not observed. The sharp, lower boundary of the parallel-bedded seismite 2 locally appears to truncate the strongly deformed seismite 1. However,

[1]GSA Data Repository item 2015135, Appendix DR1 (expanded methods and supplemental information), Figure DR1 (maps), Figure DR2 (correlation: Stenlille wells), Figure DR3 (correlation: N Albert quarry, Stenlille-1, Stenille-4, Rødby-1, and Schandelah wells, and Junglinster Heedhaff), Figure DR4 (soft-sediment deformation: Stenlille-1, Stenlille -4, and Schandelah wells), Figure DR5 (soft-sediment deformation: Grouft core and Junglinster Heedhaff), and Table DR1 (NAA analysis data), is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

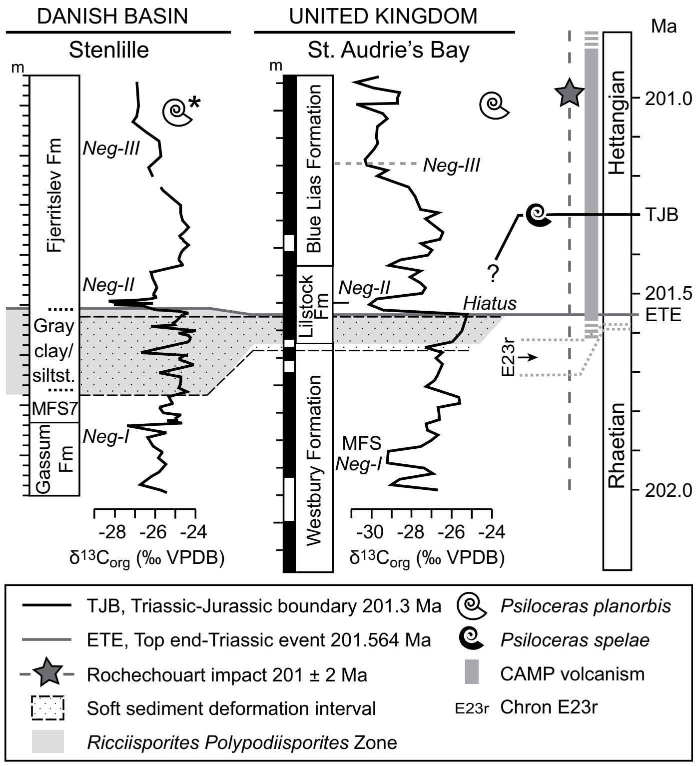

Figure 3. Biostratigraphic and chemostratigraphic correlation of seismite intervals in Denmark and United Kingdom (UK) to the end-Triassic mass extinction (ETE) (Simms, 2007; Lindström et al., 2012; Blackburn et al., 2013). Neg-I, Neg-I,I and Neg-III are negative carbon-isotope excursions of Lindström et al. (2012). MFS—maximum flooding surface; Fm.—Formation; VPDB—Vienna Peedee belemnite; CAMP—Central Atlantic magmatic province. Asterisk marks that the Danish *Psiloceras planorbis* is from Rødby-1 well; position is inferred based on biostratigraphic and chemostratigraphic correlation. Vertical scale tick marks are 1 m.

because the folding of seismite 2 mirrors the deformation in seismite 1, they likely represent the same seismic event. The contrast in deformation style is explained by increased grain size and permeability, preventing a high pore-water pressure and liquefaction of seismite 2. The overlying coarse, fluvial Boserup beds contain at least one level with soft-sediment deformation. Neither shock metamorphic structures nor iridium or other platinum group anomalies have been found at the site (Table DR1).

The Boserup beds correlate to the end-Triassic marine "gray siltstone" interval at Stenlille (~150 km to the west; event beds of Lindström et al. [2012]) (Figs. 2A, 2C and 2D; Figs. DR1, DR2, and DR4). These siltstones to very fine sandstones differ lithologically from black mudstones below (with maximum flooding event MFS7; Fig. 2A) and heterolithic mudstones above. Five to eight levels of soft-sediment deformation (liquefaction, folding, microfaulting, and pore water expulsion) are traced between the Stenlille cores, and interbedded by intervals of undisturbed strata (Fig. 2; Figs. DR2 and DR4). Wave-ripple cross-lamination indicates deposition at depths above storm wave base. In the German Basin, at least five intervals with similar soft-sediment deformation structures occur within the co-eval Triletes Beds in cores from the Schandelah, Mariental, and Rødby-1 wells. In the latter, seismites are also present within the uppermost Contorta Beds (Fig. 2; Fig. DR3). In the northeast Paris Basin, two extensively disturbed intervals are present within a transition from the Contorta Beds to the lowermost part of the Triletes Beds at Junglister Heedhaff (Kuhlmann et al., 2013; Fig. 2; Figs. DR3 and DR5). Poor exposure of the Triletes Beds at this locality hindered detailed logging, but three additional levels of small-scale folds and slumps are recorded in the Grouft well (Appendix DR1; Fig. DR5).

Temporal Constraints and Geographical Distribution of the Seismite Interval

At all localities, including the United Kingdom, the seismite beds occur predominantly within the latest Rhaetian *Ricciisporites–Polypodiisporites* (RP) Zone (Lund, 1977) or in the strata immediately below this zone (Fig. 2). The RP Zone occurs below the TJB (defined by the first occurrence of the ammonoid *Psiloceras spelae*; Hillebrandt et al., 2013), and corresponds to the marine ETE in northwest Europe (Lindström et al., 2012) (Fig. 3). This interval is further bracketed by two negative CIEs, Neg-I and Neg-II (Fig. 3). Neg-II (initial CIE of Hesselbo et al. [2002]) is generally attributed to massive CO_2 and/or methane release and regarded to have played a major part in the biotic crisis (Ruhl et al., 2011). In the United Kingdom, one additional level of soft-sediment deformation in the uppermost Langport Member (Lilstock Formation) may also be attributed to seismicity (Hallam and Wignall, 2004). Apart from that, the seismite interval encompasses strata from the upper of two magnetic reversals correlated with Chron E23r (Deenen et al., 2011) to below Neg-II (Simms, 2007) (Fig. 3). The oldest dated extrusive of the CAMP (the Tasguint basalt, Morocco) is estimated to be ~20 k.y. older than the base of Chron E23r (Blackburn et al., 2013), indicating that the most intense seismite interval, and also the RP Zone and the ETE, had a duration of <20 k.y.

Our results show that the seismites occur across an area of ~950,000 km^2 of northwest Europe (Fig. 1). From the literature, it is evident that disturbed TJB strata also have been identified further east and south in Europe, in, e.g., Poland, Hungary, Slovakia, Italy, and France, which could double the size of the affected area (Fig. 1; Appendix DR1). Deformed beds appear absent in older or younger strata, with only few local reports from the Middle Triassic (Knaust, 2002) and the upper Lower (Kullberg et al., 2001) and Middle Jurassic (Nielsen et al., 2010).

Possible Causal Mechanism

Simms (2007) favored an impact scenario and discarded the CAMP as a likely cause of the United Kingdom seismites due to the long distance between the preserved volcanics and the United Kingdom (~2000 km; Fig. 1). However, we recognize three to eight temporally separated seismite beds at each locality, indicating multiple seismic events over a longer period of time. A minimum magnitude of at least 5 ML is required to induce seismite formation (Wang and Manga, 2010). Liquefaction and seismite formation are known to occur within a 150 km radius from the epicenter of an earthquake of 7 ML, and within 500 km from the largest known fault-sourced earthquakes of ~9.5 ML (Mason et al., 2004; Wang and Manga, 2010). Figure 1 shows hypothetical positions of seismic epicenters located within a 150 km (7 ML) or 500 km (~9.5 ML) radius from each of the seismite sites, indicating that there most likely were multiple seismic epicenters (Fig. 1). This favors a connection between the seismites and CAMP formation, as first suggested by Hallam and Wignall (2004). A large igneous province may include various earthquake-generating processes (uplift, sill and dike emplacements, eruptions, and/or rifting) in its immediate surroundings, as well as causing crustal tension elsewhere. In addition, large earthquakes can trigger remote (i.e., >1500 km from the epicenter) global aftershocks that may extend in magnitude to ≤7 ML (Pollitz et al., 2012).

So far, the oldest dated CAMP lavas are all from the Northern Hemisphere and coincide in age with the ETE (Blackburn et al., 2013). However, for a large portion of the CAMP (South America and Africa) ages are poorly constrained. Onset of CAMP activity earlier than witnessed by the hitherto dated igneous record is inferred by minimum values in Sr and Os isotopes earlier in the Rhaetian, interpreted as being caused by weathering of fresh basalts (Callegaro et al., 2012). The concentration of seismites to the RP Zone has implications for the causal mechanism of the ETE. The RP Zone palynofloras reflect low-growing, fern-dominated vegetation, in stark contrast to the conifer-dominated floras before and after the ETE, indicating deforestation and restructuring of the terrestrial ecosystem prior to Neg-II. This argues for massive volcanic SO_2 emissions as a contributing factor to the biotic crisis (van de Schootbrugge et al., 2009, Lindström et al., 2012), a hypothesis supported by paleobotanical proxy data (Bacon et al., 2013) and by high magmatic sulfur concentrations (<1900 ppm) in CAMP magmas (Callegaro et al., 2014). Episodic CAMP volcanism continued for ~600 k.y. after the ETE, while the ecosystems had already started to recover (Blackburn et al., 2013). Intrusion of feeder dikes and large sills into sedimentary strata at depth during the initial stages of volcanism may have played a part in the extinction scenario (Svensen et al., 2009). Such intrusives may have formed in connection to intense seismic activity and caused venting of deleterious gases, such as halocarbons and polycyclic aromatic hydrocarbons (PAHs) that are toxic to plant and animal life and destructive to the ozone layer (Svensen et al., 2009). PAH concentrations with high coronene to benzo(a)pyrene ratios within the Triletes Beds in the German Basin suggest that contact metamorphism of organic-rich sediments occurred prior to Neg-II (van de Schootbrugge et al., 2009). The CAMP includes extensive sills and dikes that fed the basalts (Ruiz-Martínez et al., 2012; Blackburn et al., 2013), but so far none of these is dated as older than the oldest flows.

CONCLUSIONS

Despite the temporal link between the CAMP and the ETE, the causality between the formation of this large igneous province and the biotic crisis is not yet fully understood. Massive emissions of volcanic-induced CO_2 and/or methane, as indicated by carbon cycle perturbations, are believed to have caused the ETE by global warming and ocean acidification. Our data show that (1) repeated and widespread seismicity and major terrestrial ecosystem disturbances co-occurred during the latest Rhaetian, primarily prior to the most negative CIE, and (2) there is no evidence for continued seismicity in the Early Jurassic, during the remaining 600 k.y. of extrusive CAMP volcanism. This may suggest that other deleterious gases (e.g., halocarbons and PAHs), formed by magmatic intrusions into sedimentary rocks during an initial phase of the CAMP, played a part in the biotic crisis.

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REFERENCES CITED

Bacon, K.L., Belcher, C.M., Haworth, M., and McElwain, J.C., 2013, Increased atmospheric SO_2 detected from changes in leaf physiognomy across the Triassic–Jurassic boundary interval of East Greenland: PLoS ONE, v. 8, e60614, doi:10.1371/journal.pone.0060614.

Blackburn, T.J., Olsen, P.E., Bowring, S.A., McLean, N.M., Kent, D.V., Puffer, J., McHone, G., Rasbusry, E.T., and Et-Touhami, M., 2013, Zircon U-Pb geochronology links the end-Triassic extinction with the Central Atlantic Magmatic Province: Science, v. 340, p. 941–945, doi:10.1126/science.1234204.

Blakey, R., 2014, Library of paleogeography: Colorado Plateau Geosystems, Inc., http://cpgeosystems.com/paleomaps.html (accessed January 2015).

Callegaro, S., Rigo, M., Chiaradia, M., and Marzoli, A., 2012, Latest Triassic marine Sr isotopic variations, possible causes and implications: Terra Nova, v. 24, p. 130–135, doi:10.1111/j.1365-3121.2011.01046.x.

Callegaro, S., Baker, D.R., De Min, A., Marzoli, A., Geraki, K., Bertrand, H., Viti, C., and Nestola, F., 2014, Microanalyses link sulfur from large igneous provinces and Mesozoic mass extinctions: Geology, v. 42, p. 895–898, doi:10.1130/G35983.1.

Deenen, M.H.L., Krijgsman, W., and Ruhl, M., 2011, The quest for chron E23r at Partridge Island, Bay of Fundy, Canada: CAMP emplacement postdates the end-Triassic extinction event at the North American craton: Canadian Journal of Earth Sciences, v. 48, p. 1282–1291, doi:10.1139/e11-015.

Hallam, A., and Wignall, P.B., 2004, Discussion on sea-level change and facies development across potential Triassic-Jurassic boundary horizons, SW Britain: Journal of the Geological Society, v. 161, p. 1053–1056, doi:10.1144/0016-764904-069.

Hesselbo, S.P., Robinson, S.A., Surlyk, F., and Piasecki, S., 2002, Terrestrial and marine extinction at the Triassic-Jurassic boundary synchronized with major carbon-cycle perturbations: A link to initiation of massive volcanism?: Geology, v. 30, p. 251–254, doi:10.1130/0091-7613(2002)030<0251:TAMEAT>2.0.CO;2.

Hillebrandt, A.v., et al., 2013, The Global Stratotype Sections and Point (GSSP) for the base of the Jurassic System at Kuhjoch (Karwendel Mountains, Northern Calcareous Alps, Tyrol, Austria): Episodes, v. 36, p. 162–198.

Knaust, D., 2002, Pinch-and-swell structures at the Middle/Upper Muschelkalk boundary (Triassic): Evidence of earthquake effects (seismites) in the Germanic Basin: International Journal of Earth Sciences, v. 91, p. 291–303, doi:10.1007/s005310100225.

Kuhlmann, N., Thein, J., Fiebig, J., and Nagel, T., 2013, Analysis of the environmental changes from the Upper Triassic to the Lower Jurassic (T/J Boundary Event in the NE Paris Basin): Program & Abstracts, GEOFLUIDS: Lubricants of the Dynamic Earth, Joint Annual Meeting Deutsche Mineralogische Gesellschaft & Geologische Vereinigung e.V. / Sediment, Tübingen, Germany, 2013.

Kullberg, J.C., Olóriz, F., Marques, B., Gaetano, P.S., and Rocha, R.B., 2001, Flat-pebble conglomerates: A local marker for Early Jurassic seismicity related to syn-rift tectonics in the Sesimbra area (Lusitanian Basin, Portugal): Sedimentary Geology, v. 139, p. 49–70, doi:10.1016/S0037-0738(00)00160-3.

Lindström, S., van de Schootbrugge, B., Dybkjær, K., Pedersen, G.K., Fiebig, J., Nielsen, L.H., and Richoz, S., 2012, No causal link between terrestrial ecosystem change and methane release during the end-Triassic mass extinction: Geology, v. 40, p. 531–534, doi:10.1130/G32928.1.

Lund, J.J., 1977, Rhaetic to Lower Liassic palynology of the onshore south-eastern North Sea Basin: Geological Survey of Denmark, II series, v. 109, 129 p.

Mason, B.G., Pyle, D.M., and Oppenheimer, C., 2004, The size and frequency of the largest explosive eruptions on Earth: Bulletin of Volcanology, v. 66, p. 735–748, doi:10.1007/s00445-004-0355-9.

Nielsen, L.H., 2003, Late Triassic–Jurassic development of the Danish Basin and the Fennoscandian Border Zone, southern Scandinavia: Geological Survey of Denmark and Greenland Bulletin, v. 1, p. 459–526.

Nielsen, L.H., Petersen, H.I., Dybkjær, K., and Surlyk, F., 2010, Lake-mire deposition, earthquakes and wildfires along a basin margin fault: Rønne Graben, Middle Jurassic, Denmark: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 292, p. 103–126, doi:10.1016/j.palaeo.2010.03.032.

Pollitz, F.F., Stein, R.S., Sevilgen, V., and Bürgmann, R., 2012, The 11 April 2012 east Indian Ocean earthquake triggered large aftershocks worldwide: Nature, v. 490, p. 250–253, doi:10.1038/nature11504.

Ruhl, M., Bonis, N.R., Reichart, G.-J., Sinninghe Damsté, J.S., and Kürschner, W.M., 2011, Atmospheric carbon injection linked to end-Triassic mass extinction: Science, v. 333, p. 430–434, doi:10.1126/science.1204255.

Ruiz-Martínez, V.C., Torsvik, T.H., van Hinsbergen, D.J.J., and Gaina, C., 2012, Earth at 200 Ma: Global palaeogeography refined from CAMP palaeomagnetic data: Earth and Planetary Science Letters, v. 331–332, p. 67–79, doi:10.1016/j.epsl.2012.03.008.

Schmieder, M., Buchner, E., Schwartz, W.H., Trieloff, M., and Lambert, P., 2010, A Rhaetian $^{40}Ar/^{39}Ar$ age for the Rochechouart impact structure (France) and implications for the latest Triassic sedimentary record: Meteoritics & Planetary Science, v. 45, p. 1225–1242, doi:10.1111/j.1945-5100.2010.01070.x.

Simms, M.J., 2003, Uniquely extensive seismites from the latest Triassic of the United Kingdom: Evidence for bolide impact?: Geology, v. 31, p. 557–560, doi:10.1130/0091-7613(2003)031<0557:UESFTL>2.0.CO;2.

Simms, M.J., 2007, Uniquely extensive soft-sediment deformation in the Rhaetian of the UK: Evidence for earthquake or impact?: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 244, p. 407–423, doi:10.1016/j.palaeo.2006.06.037.

Svensen, H., Planke, S., Polozov, A.G., Schmidbauer, N., Corfu, F., Podladchikov, Y.Y., and Jamtveit, B., 2009, Siberian gas venting and the end-Permian environmental crisis: Earth and Planetary Science Letters, v. 277, p. 490–500, doi:10.1016/j.epsl.2008.11.015.

van de Schootbrugge, B., et al., 2009, Floral changes across the Triassic/Jurassic boundary linked to flood basalt volcanism: Nature Geoscience, v. 2, p. 589–594, doi:10.1038/ngeo577.

Wang, C.-Y., and Manga, M., 2010, Hydrologic responses to earthquakes and a general metric: Geofluids, v. 10, p. 206–216.

Wignall, P.B., and Bond, D.P.G., 2008, The end-Triassic and Early Jurassic mass extinction records in the British Isles: Proceedings of the Geologists' Association, v. 119, 73–84, doi:10.1016/S0016-7878(08)80259-3.

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