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The occurrence of seismites in the Upper Silurian Whitcliffe Formation of the old Whitcliffe quarry, Ludlow

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ROGERS, S.L.[1] (2017). The occurrence of seismites in the Upper Silurian Whitcliffe Formation of the old Whitcliffe quarry, Ludlow. *Proceedings of the Shropshire Geological Society*, **18**, 61–73. Sediments exposed in the old Whitcliffe quarry west of Ludford Bridge, Ludlow are micaceous, calcareous siltstones representing a transition from shallow marine to terrestrial environments. Two deformed beds (20 cm and 40 cm thick) are exposed, sandwiched between layers of undeformed siltstone. These are believed to be syndepositional features and are interpreted, by excluding all other possible triggering mechanisms, as seismites. Deformation takes the form of load casting (simple and pendulous), thixotropic bowls and some convolute bedding. Orientations of convolute slumping are near vertical and no direction of slumping can be inferred.

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INTRODUCTION

Two horizons of soft-sediment deformation, bounded by horizontal strata, are described within micaceous calcareous siltstones of Ludfordian age. These are exposed in the old Whitcliffe quarry, above the western bank of the River Teme, facing the town of Ludlow (Figs. 1 and 2). They have previously been documented as soft-sediment deformation and described as 'slump horizons' (Whitaker, 1962; Holland *et al*., 1963, Siveter, 2000 and Rosenbaum, 2007), and were once believed to be 'concretionary' bands (Elles & Slater, 1906) although more recent descriptions have invoked the active tectonic environment of the Silurian, with the progressive closure of the Iapetus Ocean.

The deformed sheets are confined to a relatively small area, with other examples found nearby at Clive Cottage (Dinham, Ludford) and St Giles Church, (Leintwardine, 10 km west of Ludlow) (Whitaker, 1962). The sediments at Whitcliffe were deposited on a shelf environment in close proximity to the basinal environment (Williams & Prentice, 1957; Holland & Lawson, 1963; Woodcock, 2000; Cherns *et al*., 2006) within a closing Iapetus Ocean. This has led to deductions that the deformation represents slumping due to instability of the shelf and/or to seismic liquefaction.

Convolute bedding in Ludlow age rocks has been theoretically linked to the compression which formed the Ludlow Anticline (Williams &

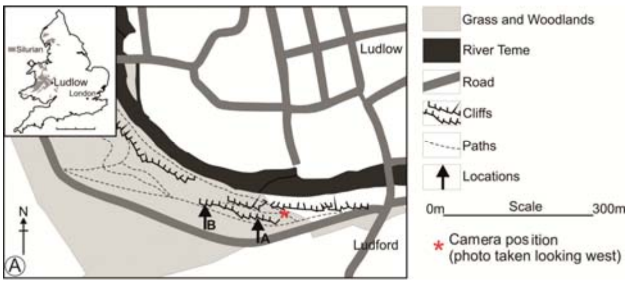

Figure 1. Map of Whitcliffe southwest of Ludlow town with locations referred to in the text highlighted (based on an Ordnance Survey/EDINA supplied service).

Figure 2. Photograph of the old Whitcliffe quarry taken from the location highlighted on the map in Fig.1. The deformed horizons are highlighted (dashed lines), the scale of the horizons (plus vegetation cover) make them difficult to see from a distance. Once closer to the face the horizons are easily identified and traced across the quarry. Person (circled) for scale (184 cm). **[Note: hard hats are necessary if you plan to approach the cliff face. Beware of, and avoid, overhangs. No hammering or collecting – this is a designated SSSI]**

Prentice, 1957). However, this compression did not occur until the culmination of the Acadian orogeny (Whitaker, 1994). As this occurred during the end of the Early Devonian (Naylor, 1971; Woodcock & Soper, 2006) it would not be possible for it to have caused the sediment deformation. Other examples of soft sediment deformation in the Upper Ludlow series have been given possible formation mechanisms of earthquake activity due to the advance of a mountain front as a result of the inversion of the Welsh Basin (King, 1994) as the Iapetus Ocean closed.

Soft-sediment deformation can often be linked to liquefaction, which results in the loss of shear resistance of the affected sediments (Owen, 2003). Liquefaction may result from many triggering events (storm events, seismic shock, uneven loading, density loading, etc.) Consequently, to designate a triggering mechanism to a deformation 'event' all possibilities must be discussed and subsequently dismissed or accepted.

This paper sets out the evidence for a seismic trigger for the deformation observed.

The structure of the deformed beds and bounding horizontal strata are described, and processes responsible for the deformation are identified and reviewed. The sedimentary composition of the lithologies is briefly described.

METHODS AND MATERIALS

Field work was undertaken within the old Whitcliffe quarry. Two stratigraphic logs were compiled taking fist-sized samples from each logged bed. Axial measurements were taken from the folded and slumped deformation horizons. From the samples obtained thin sections (30 µm thick) were made perpendicular to bedding and mounted on 2.5 x 7.6 cm slides. Two polished thin sections were also made of Samples A1 and A18. Thin sections were first investigated using a BMSZ Trinocular Stereomicroscope and subsequently using a Prior Binocular PX032POL microscope. Measurements were taken using a graticule with a precision of ± 2.5µm. Photomicrographs were taken using a Canon Powershot G5 attached to a Zeiss Max ERB microscope. A Hitachi Tabletop TM3000 at Keele University with an attached Bruker Energy Dispersive X-ray Specrometer (Quantax 70) analytical system, was used to analyse the polished thin sections for elemental compositions. Multiple point analysis were made for samples A1 and A18 of the Whitcliffe logs to determine if there are compositional changes within the succession.

GEOLOGY

The old Whitcliffe quarry displays the boundary between the Lower and Upper Whitcliffe Formations (formerly known as the Whitcliffe Group), of Ludfordian age. A limited outcrop of the Lower Whitcliffe Formation is visible within the old quarry but a larger exposure of the Lower Whitcliffe Fm. is found just to the north (20 m) along the Bread Walk, towards the River Teme. Around two metres of sedimentary rocks are seen overlain by around 18 m of the Upper Whitcliffe Formation. The Whitcliffe Formation rocks have a light grey colour when fresh, turning an olive to brownish grey with weathering through geological time. Bedding is thicker in the Lower Whitcliffe Fm. becoming increasingly thin towards the top of the Upper Whitcliffe Fm. (Fig. 3). The beds of the Whitcliffe Formation are interpreted as tempestites, indicating a storm-dominated weather system.

The Lower and Upper Whitcliffe Formations consist of micaceous, calcareous siltstones. Coquinas are observed in both formations containing the common brachiopod species *Protochonetes ludloviensis*, *Micro-sphaeridiorhynchus nucula*, *Dayia navicula* and the less common *Salopina lunata*. Coquinas and other shell assemblages are often found associated with sediment deformation and load casts.

Thin sections show that the lithology within each bed is consistent (Fig. 4): a micaceous calcareous siltstone consisting mainly of quartz grains in a calcium carbonate cement. Also present is muscovite mica of both allo- and authigenic origin. Glauconite is present in small amounts in many slides. Organic material and clays are also common and are often seen in layers associated with dewatering.

EDX investigation of the composition of A1 and A18 (Fig. 4) showed that there is no compositional difference between the Upper and Lower Whitcliffe Formations. Lithologically they are very nearly identical (Table 1 and Fig. 5).

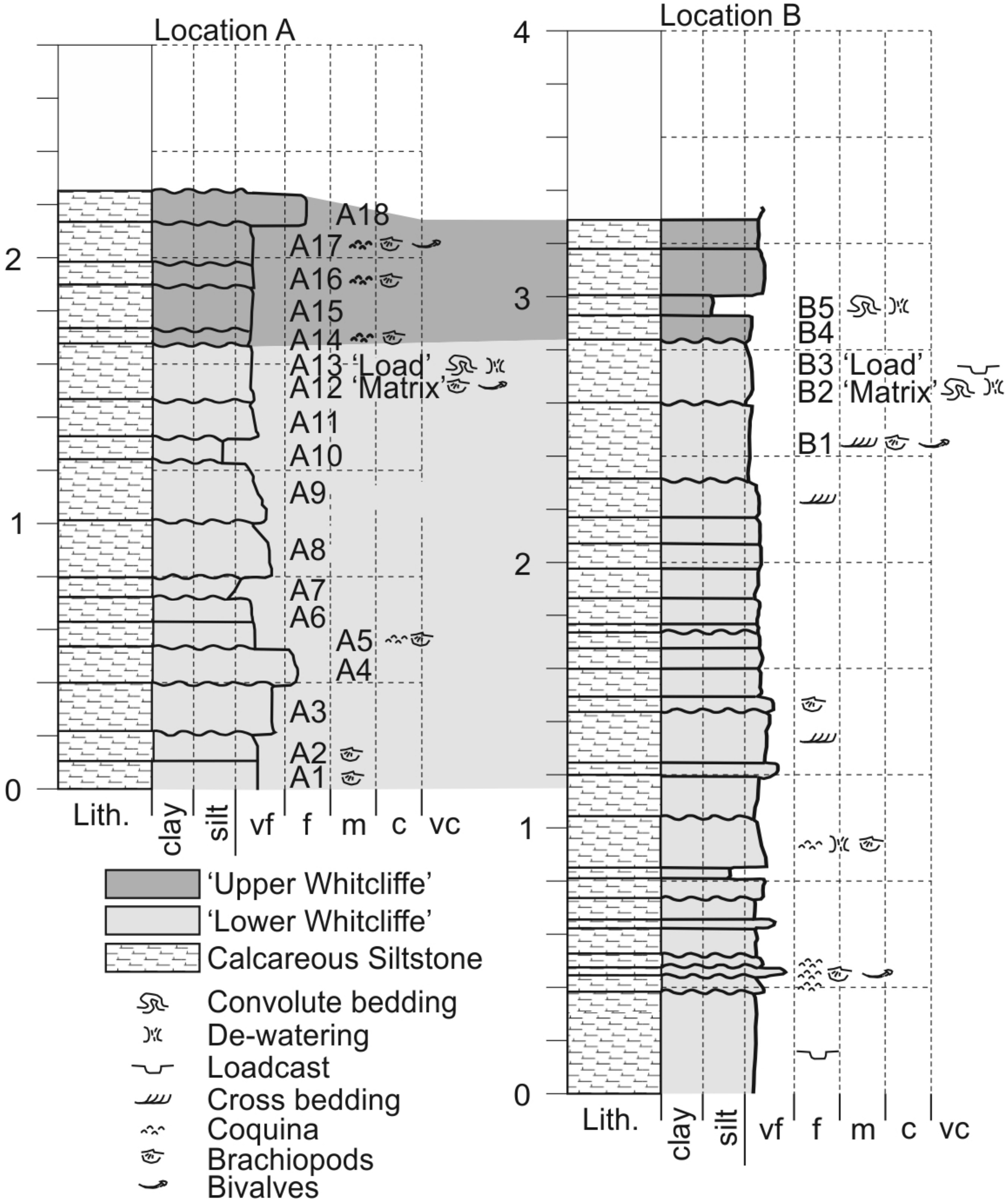

Figure 3. A correlation of sedimentary logs from locations A and B on Figure 1. Log from location A shows the Lower Whitcliffe Formation at the old Whitcliffe quarry, the 'slump horizon' (A12 'matrix' and A13 'load') and the base of the Upper Whitcliffe Formation. Numbers A1-A18 refer to bedding sample numbers. Log from location B shows the majority of the Upper Whitcliffe Formation (around 2 meters being too high to log) and the upper 'slump horizon' (B2 'matrix' and B3 'load').

Table 1

	A1-1	A1-2	A1-3	A1-4	A1-5	A1-6	A1-7	A1-8	A1-9	A1-10	Average wt%
	wt%										
O	51.98	51.48	52.12	51.78	51.8	52.03	52.05	52.09	52.22	51.75	51.93
Si	31.5	33.13	32.85	34.16	33.05	32.38	32.93	33.42	31.91	34.53	32.986
Al	5.37	5.29	5.03	4.74	5.04	5.05	4.9	4.65	5.13	4.55	4.975
Ca	4.67	3.68	3.93	3.72	4.46	4.71	4.62	4.18	5.03	3.58	4.258
Na	2.41	2.2	2.08	2.41	2.15	2.24	2.09	2.31	2.15	2.23	2.227
Fe	1.68	1.83	1.85	1.51	1.49	1.61	1.51	1.58	1.59	1.64	1.629
K	1.61	1.6	1.29	0.96	1.33	1.17	1.21	1.07	1.24	1.01	1.249
Mg	0.78	0.79	0.86	0.72	0.69	0.62	0.7	0.7	0.74	0.71	0.731
	100	100	100.01	100	100.01	99.81	100.01	100	100.01	100	99.985
	A18-1	A18-2	A18-3	A18-4	A18-5	A18-6	A18-7	A18-8	A18-9	A18-10	Average wt%
	wt%										
O	53.1	53.26	52.67	53.22	53.15	53.47	52.98	52.93	53.05	53.23	53.106
Si	29.3	26.88	30	28.38	26.32	29.87	27.54	27.57	28.5	25.46	27.982
Ca	7.02	9.23	7.08	7.64	9.69	7.63	8.52	8.72	8.1	10.49	8.412
Al	4.78	4.75	4.72	4.86	4.65	4.01	4.7	4.8	4.73	4.66	4.666
Na	1.78	1.98	2.2	1.89	2.03	1.56	2.07	2.09	1.78	2.13	1.951
Fe	1.7	1.7	1.55	1.8	1.85	1.38	1.86	1.76	1.76	1.7	1.706
K	1.27	1.32	0.97	1.33	1.31	1.23	1.4	1.21	1.19	1.23	1.246
Mg	1.06	0.87	0.81	0.89	0.99	0.85	0.92	0.93	0.88	1.1	0.93
	100.01	99.99	100	100.01	99.99	100	99.99	100.01	99.99	100	99.999

Elemental composition of Samples A-1 (Lower Whitcliffe Fm.) and A-18 (Upper Whitcliffe Fm.). Samples show very similar elemental compositions suggesting little change in sediment provenance or environmental conditions of deposition. See Figure 3 for positions of samples in relation to one another.

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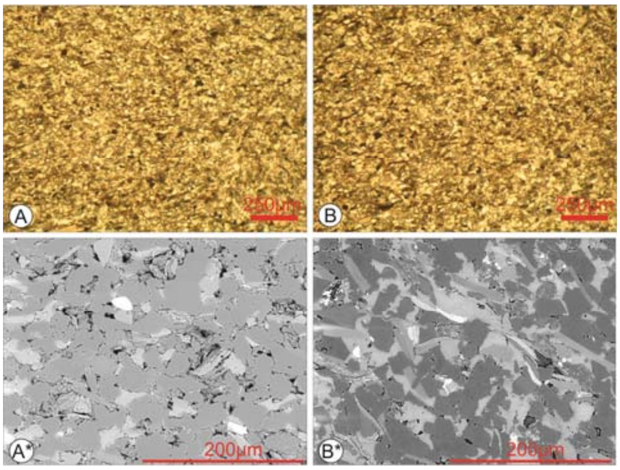

Figure 4. A and B are photomicrographs from slides of A1 and A18 respectively. A* and B* are Back Scatter Electron images of samples A1 and A18 respectively. Compositionally the samples are the same, grains are slightly smaller in A18 than A1. Note: colour difference in A* and B* is due to a difference in contrast whilst imaging.

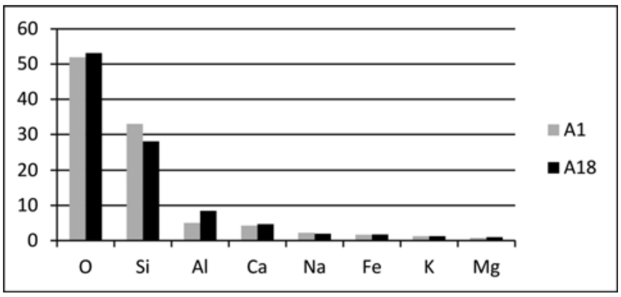

Figure 5. Bar chart summarising multi point analysis results. Y axis = weight percentage. A1 and A18 have very similar compositions, indicating that there is no compositional difference throughout the Whitcliffe Formations at the old Whitcliffe quarry.

Fossil remains in the sections comprise mainly brachiopods preserved as calcium carbonate, with most samples demonstrating recrystallisation. Spores are also quite an abundant feature and are most likely to be *Retusotriletes* cf. *warringtonii* (Richardson & Lister, 1969). Fragments of calcium phosphate are found in numerous slides and are quite possibly fragments of chitin from the carapace of eurypterids. Evidence of corals and gastropods was also found.

Sedimentary features observed were: dewatering, bioturbation, lamination and the occasional grading of laminae.

SOFT SEDIMENT DEFORMATION

Two conspicuous horizons of sediment deformation were observed within the old Whitcliffe quarry, the lowest being 1.7 m up the quarry face above the dressing floor. The horizon is around 20 cm thick and is laterally continuous for several metres before being concealed by vegetation and soil. Simple and pendulous load casts and pseudonodules as defined by Owen (2003) ranging from 10 cm to 40 cm in width are found at a high periodicity along the horizon (Fig. 6). Dewatering marks are common within the matrix layer of the horizon between the loads. This horizon can be observed again 80 m to the west of the main quarry face but is only discernable for a short distance.

The second horizon is around 4 m from the ground at the main quarry face becoming nearer to ground level to the west. This horizon is positioned at the top of the Lower Whitcliffe Formation and is used as the boundary marker between the Lower and Upper Whitcliffe Formations. The horizon is around 40 cm thick and is laterally continuous throughout the whole section. As in the lower horizon, simple and pendulous load casts and pseudonodules can be observed along this horizon. Load casts range from 20 cm up to 100 cm in width within this horizon. Convolute beds are also obvious. However, the axes of these convulsions exhibit no evidence of a dominant direction of overturning (i.e. vergence), the orientation of the fold axis being either vertical or nearly so.

In the deformed horizons some coquinas are deformed along with the sediment; in some cases the overturning of coquinas occurs. Dewatering marks were observed in most beds along the section, particularly in the upper beds.

The soft sediment deformation is exposed only as a 2D section across the quarry face and has therefore been described as such. However, it is conceivable due to the periodicity and shape of load casts that the horizons may represent thixotropic bowls in 3D (Fig. 6C) (as described by Montenat *et al*., 2007).

DISCUSSION

Load structures can develop from the mechanical instability initiated when denser sediment is deposited over less dense sediment (Selker, 1993) or when a difference in distribution of loads occurs under water saturated conditions (Owen, 2003). The driving force behind this instability is an important factor in deformation history and may aid in the identification of a triggering mechanism.

The lack of any dominant fold axial trends (they are generally vertical to very steeply dipping with no dominant vergence) indicates that deformation is not due to over-steepening of the shelf environment on which sedimentation was occurring. According to Allen (1982), other than over steepening, earthquakes are the most common causes of soft-sediment deformation.

Uneven loading arises from lateral variations in the distribution of sediments and leads to varying bulk densities. Deformation occurs when the sediments become liquefied, the lower layer being unable to support the surface loads. Uneven loading can occur even if there is no density variation between the sediment load and the substrate (Owen, 2003).

As density levels between the matrix and loads of the deformation events appear similar, uneven loading may be considered to be the driving force behind the deformation. However, it could be argued that uneven deposition of sediments is unlikely in the depositional environment interpreted for the Whitcliffe Formation and no evidence of uneven loading was observed.

Density loading is driven by a gravitationally unstable profile (i.e. a denser material lying upon a less dense material) a reverse density gradient creates a Rayleigh-Taylor instability when liquefied (Selker, 1993; Owen, 2003; Bridge & Demico, 2008).

Density loading in this manner is the preferable driving force for the load cast horizons found at Whitcliffe and surrounding areas. Due to the similarity in lithology between the loads and the matrix, the difference in density might be explained by a difference in packing or liquefaction between the layers. For a difference in packing to be responsible the load layer would have to be packed tighter than the matrix. This poses a problem as there is no evidence for a change in sedimentation or of tighter packing, although it is conceded that evidence of tighter packing can be destroyed in deformation or burial processes (Owen, 2003). It is therefore most likely that a difference in fluidisation is the cause for the divergence in density: the matrix becoming more fluidised than the load and initiating deformation.

With deformation being interpreted as being driven by density loading it is possible to infer a mechanism which initiated the loading, the mechanisms considered are those known to be common triggers.

Deformation due to Turbidity Currents

Turbidity currents are often associated with slumping. Commonly transporting sediments from shallow to basinal facies, they are driven by gravity acting upon a sediment load on a slope (King, 1994; Collinson et al., 2006). Liquefied sediment slumps and slides can occur on a slope of just 3° (Bridge & Demicco, 2008). Deposits occur when the gradient of a slope decreases causing deceleration, which in turn causes turbidity of the sediments forming slumped and folded laminae. The deformation observed at the old Whitcliffe quarry have been interpreted as load casting and the presence of a palaeoslope is not inferred from field data. Triggering by turbidity current is thereby excluded.

Deformation due to Storm Waves (Tempestites)

Aigner (1985) named deposits formed during storm events as *Tempestites*. In his work he demonstrates how the stratification characteristics of tempestites can be used to reconstruct aspects of the depositional dynamics of the sediment. The factors of deposition that can be obtained from stratification characteristics are: minimal amount of erosion during a storm event (recorded by the preservation of trace fossils); the direction of storm flow (recorded by tool marks preserved on the sole of tempestites); storm flow velocity (recorded by grain sizes of tempestites); substrate consistency (inferred from post-event faunas on top of tempestites).

Nichols (1999) describes tempestites as deposits across shelf areas caused by scouring of the coast and movement of the eroded materials where it is deposited as wave energy decreases. Tempestites can be identified by sole marks, hummocky and swaley cross stratification, normal grading and symmetrical ripples. Sediment deformation due to storm waves was described by Alfaro *et al.* (2002). They describe load casts, ball-and-pillow structures and pipes induced by the liquefaction of sandy sediments. Oceanic storms can cause the liquefaction of sediments due to *storm microseisms* which result from the collision of waves with different directions, but similar periods. This can result in shock waves on the sea bed which can induce dewatering, resulting in deformation (Darbyshire, 1962; Leppard, 1978; King, 1994).

Deposits of the Whitcliffe Formation are dominated by tempestites, many of the beds exhibiting characteristics described by Aigner (1985). Storms could therefore be a likely trigger for liquefaction and are suggested as being likely for creating the small scale dewatering and load casting found elsewhere in the section. As storm deposits are commonly observed at Whitcliffe they are unlikely to be triggers for the two main load cast horizons since, if they were, many more horizons of major soft sediment deformation would be expected. A change in lithological properties would also be expected for what would be 'larger' storm events. Triggering by storm waves is therefore unlikely.

Deformation due to Tsunami

Tsunamites are sediments deposited by a tsunami. Tsunami-related deposits of both historic and ancient events have been described by various authors (Dawson *et al*., 1996; Bondevik *et al*., 1997; Michalík, 1997; Schnyder *et al*., 2005; Kortekaas & Dawson, 2007; Puga-Bernabéu *et al*., 2007; Komatsubara *et al*., 2008). Tappin (2007) and Schnyder *et al*. (2005) express the view that tsunami events are common, recurring events. Multiple triggering mechanisms have been described: earthquake, volcanic explosion, slope instability or bolide impact (Bondevik *et al*., 1997; Shanmugam, 2006). Sediments deposited by tsunami are often similar to tempestite deposits and have sometimes been misidentified (Tappin, 2007). Several characteristics of tsunamite deposits include: a large inland extent, boulders, one or more fining up sequences, intraclasts from underlying materials, loading structures at base, bi-directional imbrication, poorly sorted sediments, diverse fossils (marine and brackish), shell rich units, and rafting of light materials (Kortekaas, 2002). Schnyder *et al*. (2005) described the features of a tsunami-induced sediment in the Boulonnais area. These were: coquina accumulations at the base of deposits, a scoured erosional surface, load structures and soft sediment deformation, the mixing of fossils and / or microfossils from different environments, a rapid lateral change of facies, and pebbles, conglomerates, reworked blocks and woody debris near the top of the sequence.

At the old Whitcliffe quarry coquinas are common at the base of the deposits and scoured erosional bases are present. These features are all observable in field, which would suggest tsunamis may be a plausible triggering mechanism. However, one would expect a difference in lithology and fossil assemblage for sediments deposited by a tsunamite compared to the "background" sediments. Differences expected would include: a mixing of fossils from different environments and pebbles, conglomerates and reworked blocks in the sediments. As neither a difference in lithology nor ecology is found, triggering by tsunami is considered unlikely.

Deformation due to Sedimentary Overloading

Sedimentary overloading is the rapid input of sediment onto water saturated sediments which induces liquefaction and soft sediment deformation (Moretti, 2001).

No evidence of rapid sedimentation or changes in sedimentation rates were observed within the section. Rapid input of sediment generally occurs in basinal environments which does not fit in with the facies interpretations for the deposition of the Whitcliffe Formation. Triggering by rapid sedimentation is thereby excluded.

Deformation due to Rapid Change in Groundwater Level

A rapid change of groundwater due to high rainfall on the hinterland would be expected to cause dewatering structures.

This trigger could be responsible for the dewatering structures observed. However, rapid change in groundwater would not cause the load casting and pseudo-nodules observed. Triggering due to rapid change in ground water level is thereby excluded.

Deformation due to Seismic Shock

Seismites are deformational structures of sediments attributed to seismic shock (Seilacher, 1969; Marjanac, 2001; Bowman *et al*., 2004; Jewell & Ettensohn, 2004; Bachmann & Aref, 2005; Gilbert *et al*., 2005; Mazumder, 2005; Simms, 2007; Spalluto *et al*., 2007) and were first described by

Seilacher (1969). Pope *et al*. (1997) describe seismites as being either primary or secondary. Primary seismites are sediments deformed in situ by a seismic event. Secondary seismites are sediments remobilised as a result of a seismic event (some turbidites, slumps, tsunamites, debris beds and homogenized units).

Structures ranging from undisturbed to faulted to liquefied deformation have been recognised as seismites (Marjanac, 2001). Depositional features of seismites are similar to those of other trigger mechanisms, as liquefaction is the chief deformation mechanism. Structures include slumping, flame structures, load casts (Marjanac, 2001 and Bowman *et al*., 2004), convolute bedding (Bowman *et al*., 2004) and sedimentary breccias (Pope *et al*., 1997). Seismically-induced slumps and slides can occur on slopes as gentle as 0.25° (Field *et al*., 1982). Slumps have also been interpreted as being formed by seismic shock on almost flat shallow sea bottoms (Rossetti & Santos, 2003).

Seven field criteria for seismites have been suggested for relating deformation features to palaeoseismic events (Bowman *et al*., 2004). These criteria are:

- Suitable location in a seismically active (at time of deformation) area,
- Suitable sediments (loosely consolidated, metastable silts and sands with low cohesion),
- Structures similar to those formed experimentally under conditions of earthquake-induced shaking (Owen, 1996), or structures similar to those reported as seismites by other authors,
- An area where slope instability caused by gravity control can be excluded,
- A stratigraphically sandwiched position,
- Lateral continuity and regional abundance,
- Cyclic repetitions of structures (cyclic repetition is expected in seismic zones).

The horizons at the old Whitcliffe quarry, meet all of these suggested criteria. The lithology and type of deformation observed are suitable, the horizons are in a stratigraphically sandwiched position and they are laterally continuous and observed elsewhere in the region. The horizons also exhibit a cyclic repetition (i.e. there are two horizons separated by non-deformed strata) and the area was seismically active at the time of their formation.

Triggering by seismic shock is therefore possible and is logically the most likely cause for the deformation observed.

Trigger for the Seismic Shock

Seismites in the Whitcliffe Formation are observable at the old Whitcliffe quarry, the Clive Cottage outcrop (less than a kilometre from Whitcliffe) and 10 km away at Leintwardine. This would suggest that the shock responsible for the seismites was localised. Due to this localised nature it is likely that the load casts represent a cross section through a field of thixotropic bowls. Montenat *et al*. (2007) suggest that thixotropic bowls occur as a result of localised, periodical liquefaction due to seismic shaking, and occur close to faults that are active during sedimentation.

Localised seismic shock in the Ludlow area during the deposition of the Whitcliffe Formation is suggested as arising from movement along the Church Stretton Fault. Woodcock (1988) and Woodcock & Gibbons (1988) suggest that the Church Stretton Fault system was operating in a strike-slip fashion during the late Katian and Hirnantian (Ashgill) and was then reactivated during the Acadian orogenic event. Naylor (1971), Woodcock (1988) and Woodcock & Gibbons (1988) give the beginning of the Acadian event as Early Devonian, whereas Tucker *et al*. (2001) give the starting date as Late Silurian. Strike-slip movement along the faults during the deposition of the Whitcliffe Formation is plausible and it is reasonable to assume such movement is the trigger for the localised, cyclic seismic activity responsible for the two horizons. Further movement of this fault during the Acadian is not recorded at this location due to the terrestrial nature of the succeeding (younger) strata. Figure 7 shows a possible, schematic, palaeogeographical reconstruction of the area.

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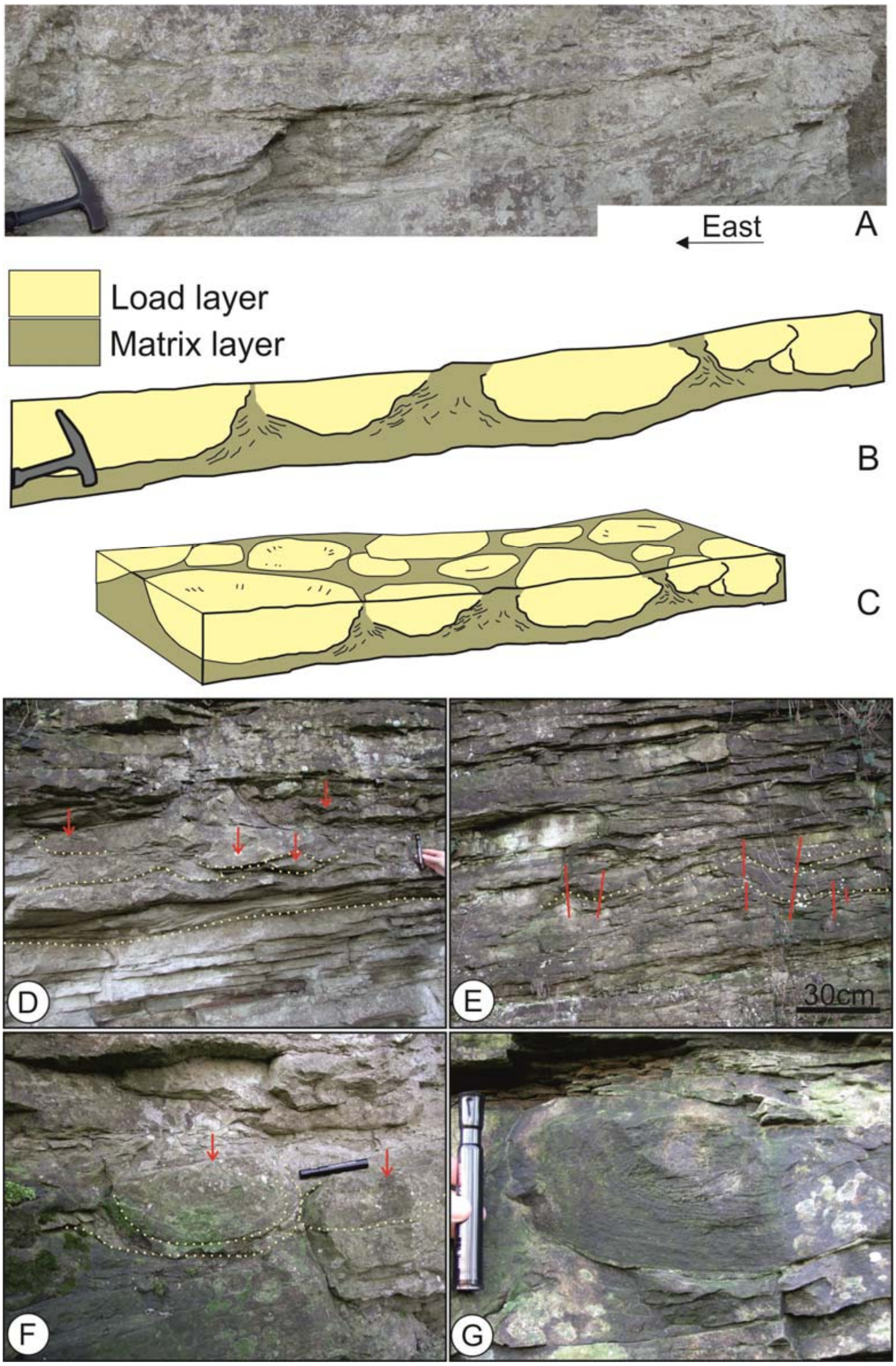

Figure 6. Examples of load casting and convolute bedding exposed in the old Whitcliffe quarry. (A) Photo montage of a well exposed section of the lower deformation horizon towards the top of the Lower Whitcliffe Formation, 2.4 m below the contact with the Upper Whitcliffe Fm. Undeformed strata can be observed both above and below the soft sedimentary deformation. Several prominent load casts with associated dewatering features are shown. Hammer head for scale (17 cm). (B) Schematic interpretation of A, the relationship between the load and matrix layers is highlighted. (C) Three dimensional interpretation of the load casts as thixotropic bowls. (D) Further examples of the load casts (arrows) with several convolute bedding planes highlighted (dashed lines). (E) Photograph showing several prominent convolute beds, highlighted as dashed lines; axial traces have been included displaying the vertical/very steep nature of the convulsions; no vergence is apparent. (F) Photograph showing the relationship between adjacent load casts (arrows); matrix material is often seen to be injected between the loads to create dewatering structures. Such structures are referred to as flame structures. (G) Photograph of an individual load cast. At this scale internal deformation can be observed within the larger structure. The small scale soft sedimentary deformation includes convolute laminae and small scale dewatering features. Pen for scale in D, F and G (14 cm).

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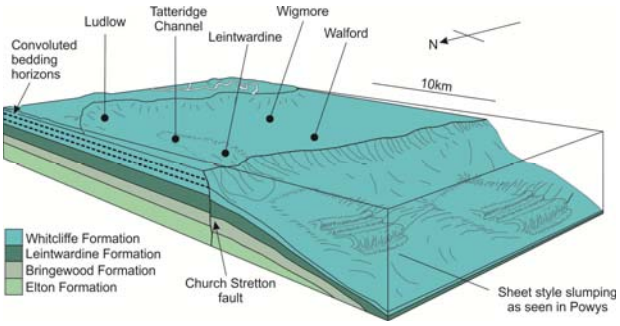

Figure 7. Schematic cartoon reconstruction of the possible palaeogeography of the Ludlow district in Whitcliffe (Ludfordian) times. The reconstruction shows how various forms of soft sediment deformation observed within the Whitcliffe Formation at different locations may have formed. The dashed lines annotated as "Convoluted bedding horizons" indicate the stratigraphic position of the beds described in this paper (and others found locally). However, rather than stretching across the entire shelf, they are envisaged as having formed within a 10 to 15 km radius of Ludlow. The Tatteridge Channel is one of several submarine channels recognised in the vicinity (see Whitaker, 1962). These were cut and filled predominantly during Lower Leintwardine times and deepened from the shelf toward the basin. In the case of the Tatteridge Channel, its northern edge was defined by a normal fault. Although the channel was mostly filled during the Lower Leintwardine its presence (and that of the associated fault) was likely to have contributed to increased instability of the shelf. Sheet style slumping in Powys (Woodcock, 1976) consists of highly deformed sediments (folds are often tight or isoclinal and are commonly recumbent) that have been described as 'slump folds'.

CONCLUSIONS

The upper Ludfordian rocks observed within the old Whitcliffe quarry, Ludlow, are micaceous calcareous siltstones, formed in a storm-dominated shallow marine to terrestrial transition. Palaeoecology is restricted; this most likely represents a brackish environment.

Soft sediment deformations observed in the old Whitcliffe quarry comprise minor dewatering events with two bands of extensive load casting accompanied by convolute bedding, which in 3D most likely represent thixotropic bowls. The deformation along these bands is considered to be due to density loading driven by differential fluidisation.

Liquefaction is believed to have been driven by a seismic shock, quite possibly due to movement along the nearby Church Stretton Fault. The deformation bands are therefore interpreted as seismites.

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