Thixotropic wedges or fluidised water-escape columns in the Charnian Supergroup at Bradgate Park

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Abstract: Discrete, funnel-shaped structures consisting of downwarped and disrupted strata are described from a restricted stratigraphical interval in the Late Neoproterozoic Charnian Supergroup, just above the base of the Bradgate Formation at exposures in Bradgate Park, in Charnwood Forest, Leicestershire. The structures occur within a deep-water marine turbidite succession and have attracted much attention, with a variety of explanations advanced to account for their origin including volcanic bomb-impacts and burrowing organisms. This article describes these structures, interprets their mode of origin, and concludes that they compare with features known as 'thixotropic wedges'. The latter have been described from various other parts of the world and are commonly placed within a category of soft-sediment deformation phenomenon known as 'seismites'. Such an association may have important implications for the style of turbidite sedimentation in the Charnian Supergroup as a whole.

In south-eastern Charnwood Forest, Bradgate Park exposes the younger formations of the Charnian Supergroup (Moseley and Ford, 1985), which is of latest Neoproterozoic (Ediacaran) age (Fig. 1). With respect to conditions of sedimentation and palaeoenvironments, one particularly interesting part of this sequence occurs within the Maplewell Group at the transition from the Beacon Hill Formation into the overlying Bradgate Formation. The latter's base is delineated by a horizon of disturbed bedding that includes the Sliding Stone Slump Breccia Member, the type locality (SK 5304 1133) for which was designated by Moseley and Ford (1985) as the partially wooded crags immediately west of the Sliding Stone enclosure (Fig. 1).

Narrow zones of strongly downwarped bedding and lamination occur in strata capping the Sliding Stone Breccia at its type locality. These structures have been a source of debate among visitors to the park for many years, but they are comparable with an unusual type of soft-sediment deformation phenomenon that has been described from a variety of sedimentary environments in other parts of the world.

Local geological setting

The downwarped strata are exposed immediately below a south-easterly dipping bedding plane at the eastern limit of the Sliding Stone Slump Breccia Member type locality (Fig. 1). The member is a prominent unit that forms an important stratigraphical marker bed throughout the outcrop of the Charnian Supergroup. However, it may also be considered as the upper and most readily mappable component of a more extensive interval of slumped and incipiently disrupted bedding which encompasses strata estimated to be about 100 m thick in the Out Woods, 5.5 km farther north (Carney, 1994). In Bradgate Park, this broader zone of disrupted bedding comprises the exposures around Old John Tower, and can be extended farther east to include the 'Park Breccia' of Moseley and Ford (1985) (Fig. 1).

In sedimentological terms as well as in age, the strata containing the downwarped structures clearly post-date the Sliding Stone Slump Breccia. The latter does, however, provide important evidence for the style of sedimentation prevailing at around that time. It commences (Fig. 2) in thick, structureless, coarse-

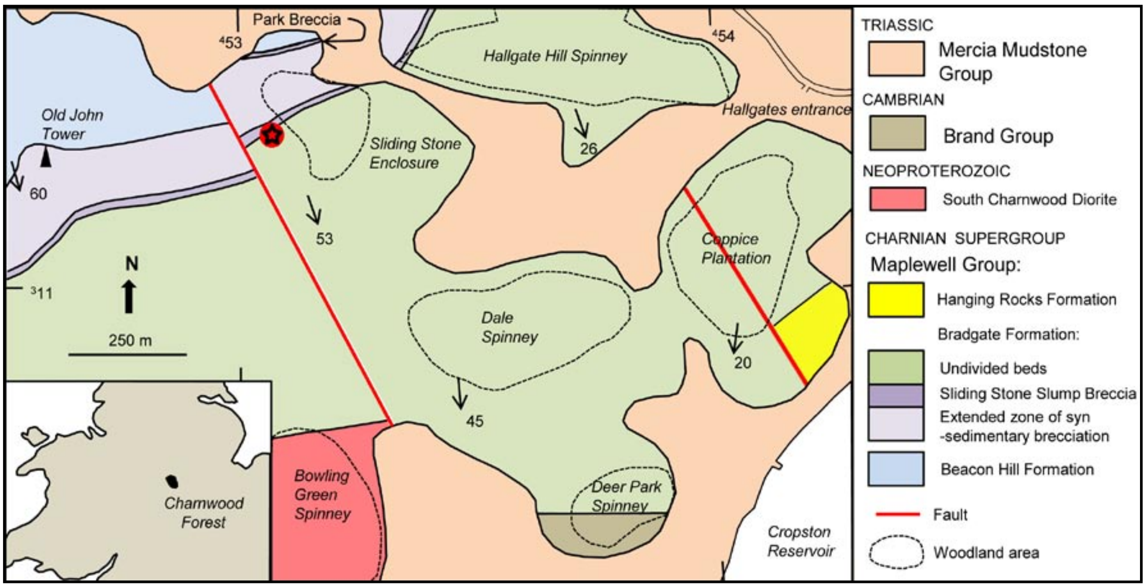

Figure 1*. Geology of eastern Bradgate Park, with a black and red star at the location of the downwarped structures (modified from BGS 1:10,000 sheet SK51SW).*

to granule-grade volcaniclastic sandstone containing abundant angular fragments and larger contorted rafts of laminated mudstone. This passes up into progressively finer grained and better sorted sandstone in which bedding and lamination become increasingly well developed. The basal facies with abundant mudstone inclusions is distinctive, and, for lithologies such as this, two alternative explanations are considered by Ogiwara and Ito (2011). They may be the deposits of a slope-collapse event (submarine landslide) that generated the *en masse* flowage of granular material containing debris of disaggregated, partially consolidated strata (the sediment rafts). Alternatively, they may represent variably consolidated strata disaggregated by in situ diapiric sedimentary injection.

The former explanation for the Sliding Stone Slump Breccia Member was favoured by Moseley and Ford (1985; 1989) and is endorsed here for two reasons. First, the unit's tabular form and its widespread distribution along a constant stratigraphical horizon throughout the Charnian Supergroup preclude a localised diapiric origin. Secondly, the changes noted above within the upper part of the unit (i.e. overlying the structureless sandstone with mudstone fragments) suggest the incoming of traction sedimentation combined with progressively waning current flow, which is typical of the 'Bouma' cycles seen in strata deposited from turbidity currents (Bouma, 1962). To account for the lower part of the member, however, a refinement of the Bouma model proposed by Shanmugam (1997) may be applicable. Thus the structureless sandstone with mudstone fragments is interpreted as a debris flow which, upon transformation into a normally graded turbidite, would give the vertical changes shown in Figure 2. This interpretation, combined with the exclusively volcanogenic nature of the grain constituents, is in keeping with the suggestion that the Charnian Supergroup accumulated either on or at the base of a submarine slope that flanked a moderately deep to deep-water turbidite basin marginal to an active volcanic arc (*e.g.* Moseley and Ford, 1985, 1989; Carney, 1999).

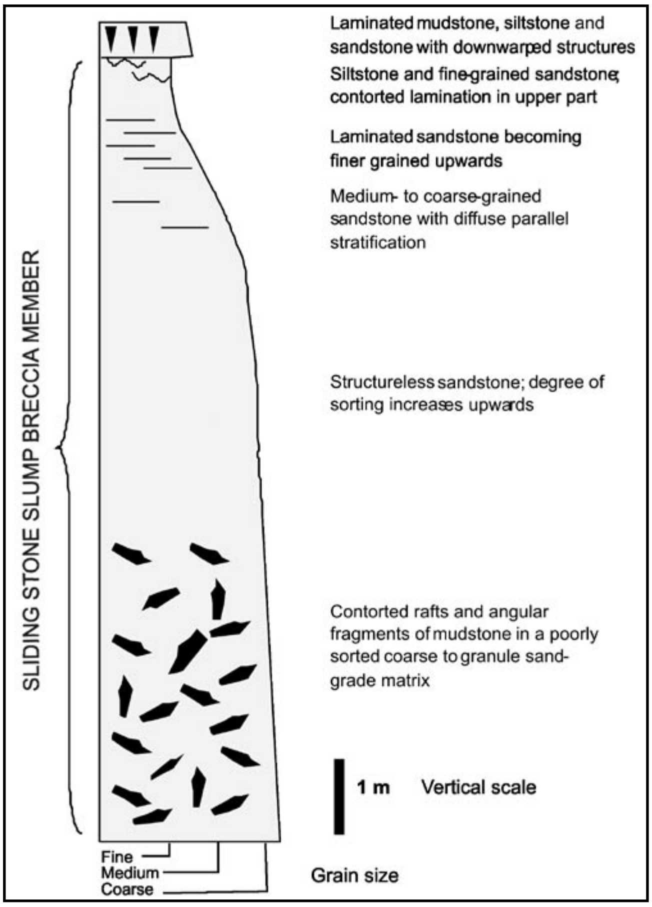

Figure 2. *Measured section in volcaniclastic strata of the Sliding Stone Slump Breccia Member at its type locality, including the overlying beds with downwarped structures.*

Description of the structures

The term 'downwarped structure' is used here in a non-genetic sense, to describe discrete, funnel-like features that form part of an otherwise relatively undeformed sequence of thinly bedded to laminated volcaniclastic mudstone, siltstone and fine-grained sandstone immediately overlying the Sliding Stone Slump Breccia Member (Fig. 2). At the locality shown in Figure 1 three such structures, spaced between 1 and 2 metres apart, all occur above the same stratigraphical horizon, which is defined by a sandstone layer about 20 mm thick

The middle of the three structures, being the better developed, forms the basis for the present description. It extends for 18 centimetres vertically, between lower and upper planar undisturbed bedding surfaces that respectively delineate the commencement and cessation of the disturbance (Fig. 3a). The structure opens upwards to a width of about 9 cm and has a slightly arcuate axis. A marked asymmetry is imparted by a) the steeper downwards curvature of strata on the right-hand (south-east) side of the structure compared to those on its left-hand side, b) the observation that strata on the right-hand side appear to be displaced upwards, compared to those on the left of the structure (Fig. 3b), and c) the steep, south-eastwards tilt of the axis of the structure (after restoration for the local tectonic dip). The left-hand margin of the structure is in part defined by syn-sedimentary microfaults with listric displacement into the axis of the structure. By contrast, its right-hand margin, although similarly microfaulted, is principally delimited by the steep downwards curvature of strata, noted above, and by the pinching out of some laminae; lower down this margin becomes serrated and ill-defined, with syn-sedimentary microfaulting present (Fig. 3b).

The upper part of the structure is defined by three sets of mudstone/siltstone laminae which show a downwards trend of increasing deformation. The highest such package, coded blue in Fig. 3b, shows only slight draw-down and no obvious thickening in the centre of the structure, although it does thin slightly where it crosses the left-hand margin. Beneath this, the green-

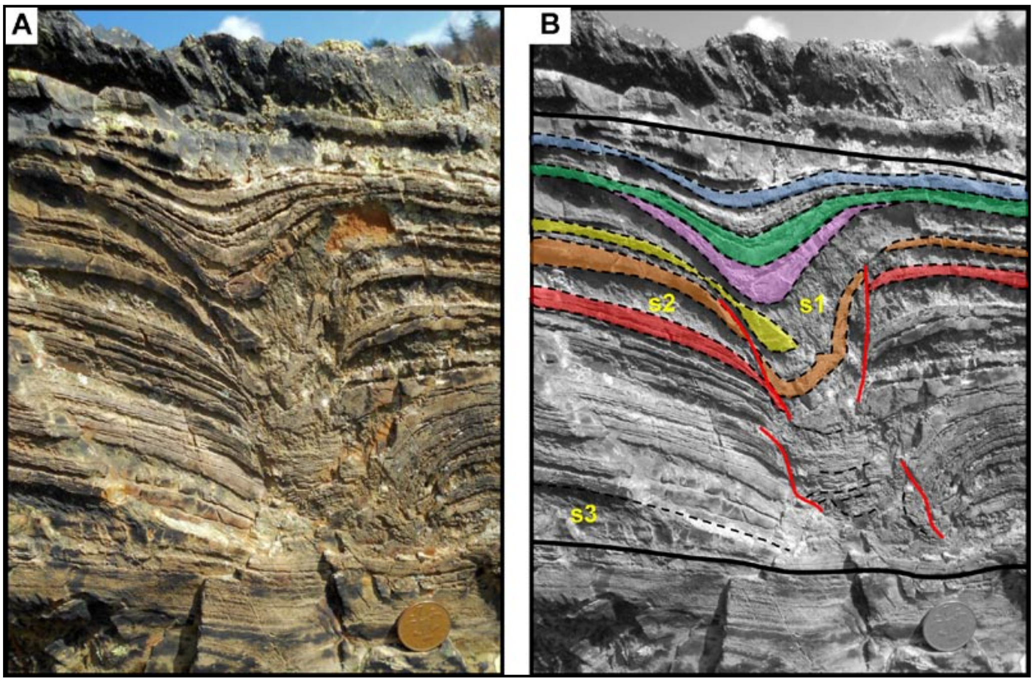

***Figure 3**. Analysis of the Bradgate Park structures. **A**: Close-up of a downwarped structure; the camera was rotated so that the strata appear in their inferred original near-horizontal attitude; the coin is 2.5 cm in diameter. **B**: Analysis of the structure shown in A; thick black lines are upper and lower bounding surfaces of the disturbed zone; black dashed lines highlight selected crumpled laminae in lower part of the structure; thin red lines are the principal syn-sedimentary microfaults; post-depositional microfaults are not highlighted; 's1-3' are prominent volcaniclastic sandstone layers. See text for explanation of other features.*

coded laminae show a greater degree of draw-down and thickening, while remaining unbroken when traced outwards into the adjacent undisturbed sequences. The laminae coloured pink in Fig. 3b thicken significantly and are drawn down into the axis of the structure, pinching out across its margins.

Mudstone strata in the lower part of the structure show the most significant disruption (Fig. 3b). A yellow-coded set becomes attenuated before disappearing in the axis of the structure. Beneath it, the brown-coded lamina becomes highly attenuated and disrupted across the left-hand margin of the structure, where it is also displaced by a syn-sedimentary microfault; on the right-hand side it becomes severely up-turned and stretched to breaking point as it crosses that margin of the structure. The lowest lamina (coded in red on Fig. 3b) that can be traced with reasonable confidence loses its identity in the central part of the structure, as do all of the strata beneath it. Here, the axial zone of the structure features crumpled, down-flexured laminae and microfaults.

Three particularly prominent sandstone beds (s1-3, Fig. 3b) show marked thickness variations with respect to the axis of the downwarped structure. The upper sandstone (s1) thickens into the axis, where it appears to engulf the termination of the yellow-coded mudstone lamina. A lower sandstone (s2) thins towards and terminates against the faulted left-hand margin of the structure, as does the basal sandstone (s3). The latter can be traced across the exposure and forms the horizon into which all three downwarped structures are considered to 'root'. It should be noted that there are many other thinner sandstone laminae; they can be distinguished on Fig. 3a by the fact that they weather-in, relative to the mudstone and siltstone beds which stand out on the surface of this exposure.

Interpretation

Previous explanations for these structures were reviewed by Carney (2010), and include: volcanic bomb-impacts, burrows, and disturbances produced by the escape of trapped water or gases. The 'bomb-impact' suggestion is implausible given the absence of large volcanic fragments in this part of the succession, and also the fact that reconstructions after folding show that this locality must have lain about 14 kilometres from the contemporary volcanic centres located in the north-western part of the Charnian Supergroup outcrop (*e.g.* Carney, 1999). An organic explanation is also dismissed; not only are these structures (Fig. 3a) atypical of burrows, but deeply-penetrating burrows on this scale are unknown in Neoproterozoic rocks where the Ediacara macrobiota, which is well represented in Bradgate Park (Boynton and Ford, 1995), consists of surface impressions and trails only.

A further comparison, with syn-sedimentary load structures of the type observed elsewhere in Bradgate Park (*e.g.* Ambrose *et al*., 2007, p.25), can also be ruled out. Load structures typically result from reverse density/porosity contrasts between adjacent beds or laminae causing, for example, the formation of a 'Rayleigh-Taylor perturbation' (Visher and Cunningham, 1981). This commonly results in the downwards penetration of sandstone as lobe-like masses into an adjacent underlying mudstone. By contrast, Fig. 3a shows that the downwarped structure is considerably more complex than this, affecting numerous sedimentary layers with a variety of physical properties ranging from mudstone through to siltstone and fine-grained volcaniclastic sandstone. There are, however, two further, interrelated categories of soft-sediment deformation that can be considered.

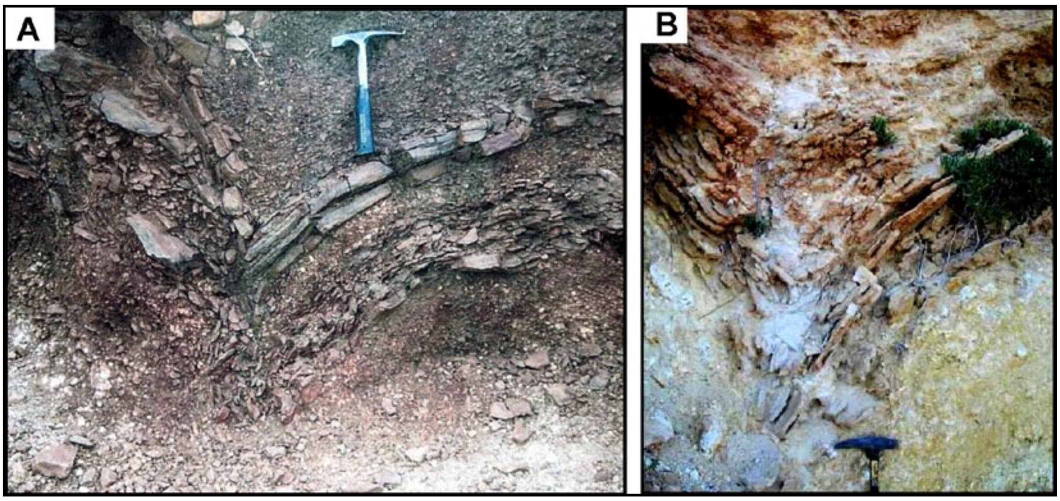

***Figure** 4. Comparisons with thixotropic wedges. **A**: Structure compared to a thixotropic wedge and attributed to syn-sedimentary seismicity within argillites of the Mesoproterozoic Lokapur Subgroup in southern India (photo: S. Patil Pillai). **B**: Thixotropic wedge in Pliocene marls of the Trubi Formation, south-eastern Sicily, attributed to nearby seismicity (after Pirrotta and Barbano, 2011).*

Thixotropic wedges

'Thixotropic wedges' are narrow, discrete funnel-like structures featuring laminae that show draw-down and disruption (*e.g.* Montenat *et al*., 2007) as a result of complex processes associated with sediment mobilisation (see below). They can occur over a range of environments and ages, and two examples are shown for comparison in Figures 4a and b. The former is from thinly interbedded shales and siltstones of Mesoproterozoic age, inferred to have accumulated as mudflats in a shallow water environment (Patil Pillai and Kale, 2011). The second example (Fig. 4b) is from a Pliocene, carbonate-dominated sedimentary sequence deposited in moderately deep waters (Pirrotta and Barbano, 2011). This latter example most resembles the Bradgate Park structure: it has a well-defined lower, chaotic infill, which includes downwarped, detached remnants of laminae, and an upper zone in which sedimentary layers show progressively less deformation, but nevertheless exhibit draw-down across the axis of the involution.

Sediments containing water are able to deform like this if they exhibit thixotropy, which is defined as the property of materials that are stable when at rest under normal conditions, but which then become liquefied and are capable of flowage when shaken, agitated, or otherwise stressed in the absence of any introduced fluid (*e.g.* Boswell, 1951; see also the review by Barnes, 1997). Gels and colloids are thixotropic materials that exhibit these properties; however, Boswell (1949) stated that all sediments, barring clean (i.e. mud-free) sands, can behave similarly under appropriate conditions, with clays showing the strongest properties in this respect. The experiments conducted by Boswell (1951) found that shaking was a particularly effective mechanism for bringing about the virtually instantaneous mobilisation of thixotropic sediments. Moreover, shaking is directly applicable to geological situations and is the favoured triggering mechanism for settings in which water-saturated, thixotropic sediments are suggested to have been mobilised by seismic activity (*e.g.* Montenat *et al*., 2007).

Where thixotropic sediments become mobilised, liquefaction occurs in an essentially closed system. The process is driven by the breakdown of the grain framework and transfer of grain support to the pore fluid, and could be caused by an increase in pore fluid pressure as a result of seismically-induced shaking (Ishihara, 1993; Owen, 1996). In a broader context, however, it is also possible that liquefied water/sediment mixes generated through shaking in one part of a thixotropic sediment column could migrate laterally into another part. In the latter areas, the injection of an extraneous water-sediment mix would result in the complementary process of fluidisation.

Fluidisation

The post-depositional escape of fluidised water-sediment mixes typically results in up-domed laminae of the type commonly found in the root zones of sand volcanoes (*e.g.* Montenat *et al*., 2007). The fluidisation experiments of Frey *et al*. (2009), however, are more relevant to the features under discussion here, because they show that under certain conditions laminae can also be drawn downwards. In one experiment (Frey *et al*., 2009), water was initially injected upwards into the base of a static, sand-rich sedimentary sequence with thin intercalated silt layers (Fig. 5a). The added water resulted in pore expansion and eventual fluidisation of a column of sand, but as barriers to flow (the silt layers) were encountered the fluidised column turned and circulated downwards, producing a water-and-sediment convection cell. The force exerted by the convecting fluid first up-domed the overlying silt layer, and then breached it, causing draw-down of adjacent laminae into the zone of fluid injection (Fig. 5b). This process was repeated as the cell migrated upwards, through successive silt-barriers, resulting in a funnel-shaped column with a width of approximately 3 cm composed of homogeneous sand. The adjacent silty layers arched downward toward the margins of the column, and terminated abruptly at its walls, which were relatively straight and vertical (Fig. 5c). Frey *et al*. (2009) noted that although sand volcanoes were commonly produced at the surface of the injection column, most of the fluidised sand was retained within it.

The Bradgate Park structures (Figs. 3a, b) show some similarities to those produced experimentally by Frey *et al*. (2009); for example, the thinning-out of some sandstone layers (s1, s3) towards the downwarped structure and complementary draw-down of overlying mudstone and siltstone beds and laminae. Although the model of Frey *et al*. (2009) does feature layered sediments, it is sand-dominated and thus not strictly comparable to the varied mud/silt/sand sequence seen at Bradgate Park. In this more complex lithological situation, where there are rapid alternations between relatively thin sand and mud/silt layers (Fig. 3a), it is unlikely that the processes modelled by Frey *et al*. could operate efficiently unless other factors were involved.

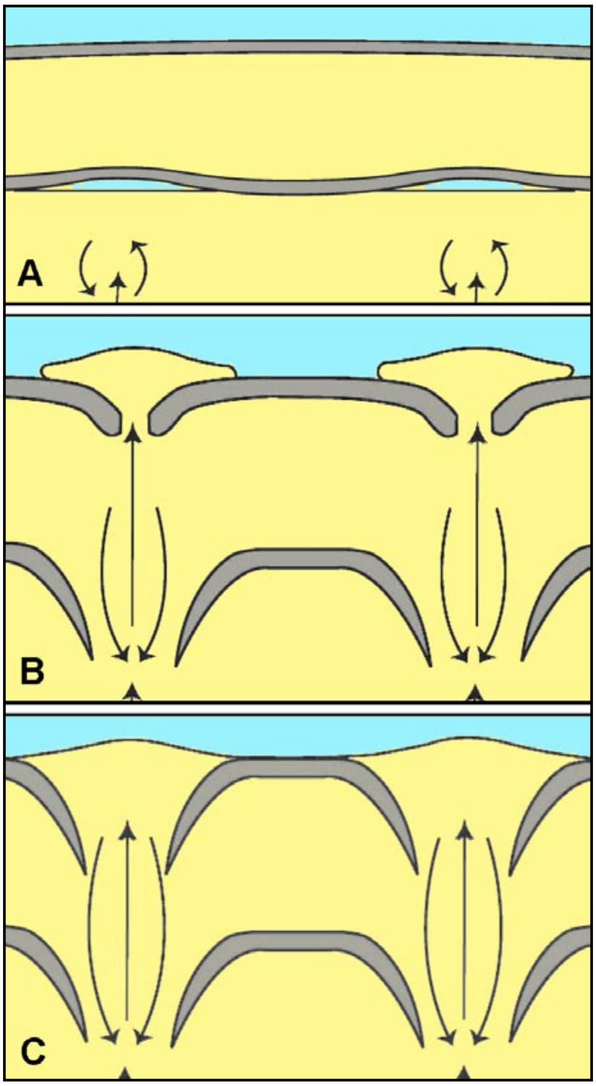

***Figure** 5. Sequence of events during water-escape experiments in sediments composed of sand and silt - the shaded layers (after Frey et al., 2009). **A**: Initial fluidization due to upwards injection of water into lower layers; water collects in void beneath up-domed silt layer. **B**: Continued fluidization results in a water/sediment convection cell, causing the progressive draw-down of silt layers. **C**: Stable column of circulating sediment and water established for as long as fluid injection process was continued.*

One possible supplementary mechanism is suggested by Thorsson *et al*. (1986), from studies of Late Quaternary clays, silts, sands and gravels showing wedge-shaped zones of downwarped strata. In the 3-D outcrops available for that study, those structures correspond to tensional fissures inferred to have opened during seismically induced shaking. It was suggested that the fissures allowed mobilised sand from underlying overpressured strata to be injected upwards as fluidised columns. This process caused the mobilised sand layers to thin towards the fissures, and overlying silty strata to collapse into them, resulting in microfaulting and downwarped laminae similar to the features highlighted in Figure 3b.

No fissuring could be identified in association with the Bradgate Park structures, for which only 2-D exposure was available (Fig. 3a); however, one other feature of the Thorsson *et al.* (1986) model that bears comparison is their description of an upper filled ‘sediment plug’ in which strongly downwarped beds thicken into the axis of the fluidised columns and pinch out along their margins. These geometrical relationships recall similarities to the upper pink, green and blue-coded laminae in Figure 3b, for which two explanations are possible. If these upper sediment layers constitute a post-deformational sedimentary infill, as in the Thorsson *et al*. examples, they may represent muddy or silty, distal turbidites that had sloughed into the still-open fissure and progressively filled it. Alternatively, they could represent part of the sedimentary sequence into which tensional fissuring had not propagated, but which nevertheless were drawn down above the disturbance, deforming plastically as they did so to produce the observed trend of thickening.

The absence of sand or silt volcano edifices in the Bradgate Park occurrences suggests that any fluidised sand drawn into the downwarped structures did not reach the surface but may have migrated laterally along it, perhaps to be vented upwards elsewhere.

Discussion

The Bradgate Park downwarped structures are suggested to most closely resemble the category of discrete, soft sediment deformation phenomenon that have been given the part-genetic, part-descriptive name of ‘thixotropic wedge’. Such structures are unusual in the geological record, and are postulated to have resulted from the mobilisation of thixotropic sediments upon seismically induced shaking (*e.g.* Montenat *et al*., 2007). With this interpretation it can be suggested that soon after deposition parts of the Charnian sedimentary sequence were capable of being liquefied, to flow like fluids over a relatively short period of time before returning to a stable condition after the triggering movements ceased.

Features similar to thixotropic wedges were produced by the fluidisation experiments of Frey *et al*. (2009). Although such experiments were performed in the absence of shaking, the results (Figs. 5a-c) nevertheless imply that fluidisation may be a process complementary to liquefaction during the formation of thixotropic wedges. This linkage is likely to occur when water-saturated, thixotropic sediment becomes liquefied upon seismic shaking and is then injected into a separate part of the sediment column (*e.g.* Thorsson *et al*., 1986). Thus for the Bradgate Park structures a possible scenario is that overpressuring facilitated the lateral movement of mobilised sediment, which then was evacuated upwards as narrow, fluidised columns into tensional fissures formed during the same bout of seismicity. After upwards injection was largely completed, the more coherent silt or clay-rich laminae deformed plastically and collapsed into the fissures, resulting in the formation of complex, downwarped structures comparable to a 'thixotropic wedge'.

The observed asymmetry of the Bradgate Park structures suggests a superimposed component of compression, directed from right to left in Fig. 3a. If occurring towards the end of the seismic event, this may have been the mechanism that closed off the circulation of fluidised material, resulting in the cessation of collapse and downwarping. Late compression appears to be at odds with the tensional model proposed above; however, it could be compatible with a sideways seismic shaking motion within water-saturated sea-floor sediments transmitted by the action of P-waves, which change the volume of intervening material by alternating expansion and compression (Milsom, 2003).

Most authors refer thixotropic wedges to the spectrum of soft-sediment deformation phenomenon known as 'seismites' (Seilacher, 1969), which are triggered by earthquake-induced shaking of water-saturated sediments. Indeed, the scheme of Montenat *et al*. (2007; their fig. 3) goes as far as classifying thixotropic wedges within their category of 'seismites *sensu stricto'*, together with other features such as sand volcanoes and diapirs. It is thought that seismic shocks generate a recurrent horizontal shear strain effect in unconsolidated thixotropic deposits (Davidovici, 1985), causing an instantaneous segregation of the liquid from the solid sedimentary phase. According to Montenat *et al*. (2007), the sediments most susceptible to this type of deformation are fine-grained materials with contrasting granulometry, such as alternating beds of mud, silt and fine sand. In such sequences, which greatly resemble the example from Bradgate Park discussed here, the phenomenon is characterized by: (1) destruction of the sediment structures, (2) modification of pore-fluid pressure, (3) refitting of grains which leads to an increase in the density of the granular phase, and (4) overpressuring of a water-saturated sedimentary sequence, which is responsible for the phenomena of expulsion and/or injection of a liquefied phase (water+smallest grains and mud), generating the seismite structures. These phenomena have been modelled in numerous studies, with experiments and measurements reproducing different seismite structures (Kuenen, 1958; Owen, 1987).

A caveat to this is that 'seismite' is a strongly genetic term, relating more to a cause than to a diagnostic rock fabric or structure. It should therefore be applied with caution, particularly since phenomenon caused by fluidisation and fluid expulsion can occur independently of seismicity (see reviews in Owen *et al*., 2011; Moretti and Ronchi, 2011). For example, fluidisation in saturated sediments is commonly attributed to water escapes associated with overloading of a sequence upon the rapid emplacement of turbidites (Keunen, 1958; Moretti and Ronchi, 2007). Such a mechanism would be in keeping with the Charnian depositional environment (Moseley and Ford, 1989; Carney, 1999); however, the downwarped structures featured in Figs 3a and b were clearly formed *after* a major episode of sediment-gravity flowage (the Sliding Stone Slump Breccia Member; Fig. 2), and there is no evidence for a similar event occurring close above them.

As noted by Montenat *et al*. (2007), there are cases where the identification of seismites remains hypothetical through a lack of complete knowledge of the geological context. Similarly, Pirrotta and Barbano (2011) suggest that the causative mechanism for soft-sediment deformation structures is generally not directly recognisable by the analysis of their morphologies; it requires a paleoenvironmental reconstruction of the site, at the moment of the sediment deposition, and a critical analysis aimed at excluding the other causes. It is therefore often more feasible to recognise seismically-triggered soft-sediment structures in modern earthquake zones, and when this is done features that include thixotropic wedges are commonly identified (*e.g.* Thorsson *et al*., 1986; Pirrotta and Barbano, 2011). Where contemporary seismicity cannot be established, one criterion in favour of a seismic origin, cited by Moretti and Ronchi (2011), is where undeformed beds identical in lithology and facies to the deformed horizon occur above and below it. This is the case for the observed structures in Bradgate Park, which are both underlain and overlain by relatively undisturbed strata (Fig. 3a).

The possibility that some structures described as thixotropic wedges may in fact be ice-wedge casts, which are of similar morphology, has been considered by many workers. However, such an origin can usually be ruled out when climatic, morphologic and chronological lines of evidence are introduced, as discussed by Thorsson *et al*. (1986). For the Bradgate Park structures a glacigenic origin can be more easily dismissed. Ice-wedge casts are commonly held to form through a process of thermal contraction accompanied by seasonal melting and freezing in permafrost environments, although the precise mechanisms are not as yet fully understood (*e.g.* Murton and Kolstrup, 2003). The Bradgate Park structures, however, formed in water-saturated sediments deposited on the floor or lower slopes of a marine turbidite basin in which palaeotemperatures would not have been significantly affected by short-term fluctuations.

Conclusions

The downwarped structures in the Charnian Supergroup at Bradgate Park strongly resemble 'thixotropic wedges'; a type of soft-sediment deformation structure falling within the category of 'seismite' according to Montenat *et al.* (2007). Seismites can arise within a water-saturated sediment column that has inherent thixotropic properties such that, when shaken during an earthquake of sufficient magnitude, it becomes mobilised due to the complementary processes of liquefaction and fluidisation.

This origin for the Bradgate Park downwarped structures is in accordance with suggestions that seismicity is one of the main triggering mechanisms for generating a whole range of soft sediment deformation phenomenon in turbidite basins (Montenat *et al.*, 2007). Although many of the supposed seismogenic disturbances reviewed by those authors are found in the Charnian Supergroup, it is accepted that for ancient rock sequences the involvement of seismicity will always be difficult to prove, relying as it does on circumstantial rather than conclusive evidence. A seismically active, island arc-type environment is, however, in keeping with the nature of massive andesitic and dacitic igneous rocks interpreted to represent contemporary volcanic centres in the north-western part of Charnwood Forest (Moseley and Ford, 1989; Carney, 1999).

One non-seismic cause of instability within turbidite basins which should be considered is overloading of the sedimentary sequence due to rapid deposition of the beds above, as pointed out by Moretti and Ronchi (2011). If the Bradgate Park downwarped structures are indeed 'seismites' *sensu* Montenat *et* al. (2007), this mechanism may not be applicable; however, a holistic approach, which includes the possibility of both seismic and non-seismic triggering factors, would be advisable when attempting to explain the many other types of soft-sediment deformation seen in Charnian strata.

Following from this, a possible sequence of events for the passage of sedimentation shown in Fig. 2 is that, firstly, part of the Charnian sedimentary sequence became destabilised, either through seismicity or overloading, or a combination of both. This caused a major slide to develop on the submarine slope, resulting in the disaggregation and widespread gravity flowage of unconsolidated sediments, to be emplaced as the Sliding Stone Slump Breccia Member. Subsequent seismic activity may have been the more direct cause of limited fissuring and mobilisation within an overlying package of thixotropic sediments, forming the downwarped structures described here.

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