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Origin and significance of soft-sediment deformation in the Old Red Sandstone of central South Wales, UK

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ABSTRACT

Vertically oriented water-escape cusps are the most common type of soft-sediment deformation structure in sandstone-rich intervals of the fluvial Brownstones and Senni Formations (Cosheston Subgroup, Daugleddau Group) of the Lower Old Red Sandstone in the central Brecon Beacons and eastern Black Mountains, South Wales. The structures are widely distributed and occur at several stratigraphical levels. They can be divided into two styles. (1) Small-scale (height less than a single bed), isolated water-escape cusps formed when loosely packed sediment deposited rapidly in flood events liquefied in advance of subsequent flood events or pulses, causing localised fluidization due to the escape of excess pore water. Inclined cusps higher in some beds confirm the relationship of this deformation style to active flood events. (2) Horizons of larger-scale (occupying the entire bed thickness), laterally continuous water-escape cusps and fold trains can be traced for hundreds of metres to kilometres and result from widespread liquefaction in response to earthquakes. A lack of overturning indicates that their formation did not coincide with active flow conditions. Further detailed mapping is needed to clarify the continuity and extent of such structures and their relationship to faults that may have been active during sedimentation. The occurrence of triggers capable of causing liquefaction in granular materials provides a greater control on the occurrence of soft-sediment deformation than do lithological controls such as grain size or interbedding of sandstone and mudstone. The findings are broadly consistent with interpretations of soft-sediment deformation in the Cosheston Subgroup in Pembrokeshire, SW Wales.

1. Introduction

Soft-sediment deformation refers to the deformation of unconsolidated or partially lithified sediments while they are at or close to the sediment surface, during or shortly after sedimentation (Owen, 1987; Maltman, 1994; Van Loon, 2009). Deformation occurs while sediment is temporarily transformed from a solid-like to a liquid-like state, enabling it to respond to weak stresses that would not normally cause deformation (Allen, 1982; Maltman and Bolton, 2003). The change of state, referred to as liquidization by Allen (1977) and deformation mechanism by Owen (1987), can be brought about by different processes; in sands the main processes are liquefaction and fluidization (Lowe, 1975, 1976; Allen, 1982; Owen and Moretti, 2011). Liquefaction is a temporary loss of strength due to the loss of grain–grain contacts, associated with an increase in pore-fluid pressure. In modern sediments, liquefaction may be initiated (triggered) by processes such as groundwater movement, wave action, hydraulic stresses associated with flood-induced turbulence, rapid sedimentation or, most commonly, seismic shaking (e.g. Quigley et al., 2013). Fluidization is a reduction in sediment strength associated with the upward movement of fluid through sediment. Fluidization may develop in response to groundwater movements (Guhman and Pederson, 1992; Li et al., 1996; Massari et al., 2001) or locally due to the upward escape of excess pore water (water escape), which can occur following liquefaction when grains re-settle to a tighter packing (reduced porosity) than they had previously (Lowe, 1975). Thus, deformation enabled by liquefaction and fluidization can be closely related. The stress systems that drive deformation while sediment is liquidized (driving force systems) include gravity acting on slopes, uneven loading of a surface (e.g. bedform topography), density contrasts within the sediment pile (e.g. denser sand overlying mud), and lateral shear such as that related to current flow (Owen, 1996).

For soft-sediment deformation to occur in sandy deposits, it is normally necessary for a driving force system to bring about deformation while a deformation mechanism operates, in many cases initiated by some form of trigger (Owen, 1987; Owen and Moretti, 2011), but it can be a challenge to infer these three

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components from structures preserved in the geological record. The geometry of deformation structures indicates the orientation of stresses during deformation and the likely origin of the stress system. With regard to deformation mechanisms, a working distinction can be made between the roles of liquefaction and fluidization in that liquefaction typically deforms – but does not destroy – primary stratification, is usually pervasive in its occurrence, and often results in deformation that increases upwards in intensity since the duration of the liquefied state is greater for the upper parts of a liquefied interval. In contrast, the effects of fluidization are often localised, may result in the complete loss of primary stratification and are greatest in the zone of fluid escape, which will typically have a vertical orientation. The identity of the triggering agent is perhaps the most difficult aspect to reconstruct with confidence (Owen et al., 2011); the most fruitful approaches involve analysis of the spatial and stratigraphical distribution of deformation structures, the palaeoenvironmental setting of the deposits in which they occur, and their proximity to faults that may have been active during sedimentation (Owen and Moretti, 2011).

This paper presents the results of a reconnaissance survey for soft-sediment deformation structures in the Old Red Sandstone of the Brecon Beacons and Black Mountains, central South Wales, in the central part of the Anglo-Welsh Basin (Williams et al., 2004; Barclay et al., 2005). The focus is on the upper part of the Lower Old Red Sandstone (Cosheston Subgroup of the Daugleddau Group: Barclay et al., 2015), primarily the Brownstones Formation but also parts of the Senni Formation (Table 1). Soft-sediment deformation structures are described from several sites at different stratigraphical levels and their implications for Old Red Sandstone depositional and palaeoenvironmental conditions are considered.

2. Soft-sediment deformation in sandy fluvial deposits

Soft-sediment deformation in sands is most likely to occur when the following conditions are satisfied (Owen and Moretti, 2011). (1) *Sediment characteristics render the sediment susceptible to liquefaction or fluidization (liquidization).* Coarse silt to medium sand are the optimum grain sizes for liquidization; cohesion in finer-grained sediments inhibits grain separation, whereas the higher settling velocity of coarser particles reduces the duration of the liquefied state or increases the throughflow rate needed to generate fluidization. Liquidization is more likely in sediment with high porosity and permeability, which can be caused by rapid sedimentation or deposition as cross-stratification. Liquidization is only likely to occur in subaqueous depositional environments or saturated sediments beneath the water table, since liquefaction occurs only in saturated sand and fluidization requires the movement of fluid through the sediment. Permeability barriers that impede the vertical movement of fluid through the sediment pile, such as mud laminae within sand deposits, lead to a build-up of pore-fluid pressure in underlying sediments, increasing the likelihood of liquefaction or fluidization occurring. (2) *Suitable driving forces are present* such as slopes, including those associated with surface bedforms, bulk density variations such as those due to the interbedding of mud and sand, or vigorous current flow while sediment is mobilised. The through-flow of fluid responsible for fluidization represents the driving force for deformation in water-escape structures. (3) *Potential triggers exist*, either external to the depositional environment such as seismic events (exogenic triggers) or sedimentary events involving rapid sedimentation or rapid, turbulent flows (endogenic triggers).

Many of these conditions are satisfied in sandy fluvial deposits, particularly those in which sand was deposited rapidly in flood events, and soft-sediment deformation structures are common in many fluvial successions, including Proterozoic successions in northern Norway (Røe and Hermansen, 2006), the Neoproterozoic Torridonian succession of NW Scotland, in some parts of which well over half of the vertical succession is affected by soft-sediment deformation (Selley, 1969; Stewart, 2002; Owen and Santos, 2014), the Cambrian Guarda Velha Formation in Brazil (Santos et al., 2012), the Carboniferous Fell Sandstone of NE England (Leeder, 1987), and modern river deposits (Li et al., 1996). There have, however, been few accounts of soft-sediment deformation in the fluvial Old Red Sandstone of the Anglo-Welsh Basin, despite the sandy character of parts of the succession, the close interbedding of sand and mud in much of the succession, an abundance of cross-bedding, and increasing evidence for the role of tectonics during sedimentation (Friend et al., 2000; Hillier and Williams, 2004).

One unit in the Old Red Sandstone of the Anglo-Welsh Basin from which abundant soft-sediment deformation has been described is the Cosheston 'Group' in south Pembrokeshire (Thomas et al., 2006). The cumulative thickness of deformed intervals in lower parts of the succession is estimated at 20% of the 435–550 m thickness of the Llanstadwell Formation and 29.5% of the 540–600 m thickness of the Mill Bay Formation (Thomas et al., 2006). The Mill Bay Formation comprises very fine to coarse grained sandstones interbedded with siltstones and intraformational conglomerates and is broadly equivalent to the Senni Formation of central South Wales (Barclay et al., 2015). Thomas et al. (2006) attributed most (98%) of the soft-sediment deformation in the Mill Bay Formation to vertical movements of sediment (foundering) and water (water escape) and distinguished two categories of soft-sediment deformation structures. (1) Founder folds in parallel laminated sandstone are similar to water-escape 'cusps' (Selley et al., 1963; Owen, 1995a). They either die out or are truncated upwards and are attributed to water escape, although the preservation of stratification suggests that full fluidization may rarely have developed. (2) A variety of types of load structures (Owen, 2003) occur in heterolithic facies, including two ball-and-pillow horizons, each several metres thick, termed 'pillow beds'. The 'pillow beds' and the water-escape cusps are attributed by

Table 1
Stratigraphy of the Old Red Sandstone in central South Wales (after Barclay et al., 2015).

<table>
<tr><td colspan="2">Carboniferous</td><td colspan="4">Carboniferous Limestone and younger rocks</td></tr>
<tr><td rowspan="5">Devonian</td><td rowspan="2">Upper</td><td>Grey Grits Fm.</td><td colspan="2" rowspan="2">Brecon Beacons Group
(Upper Old Red Sandstone)</td><td rowspan="6">Old Red Sandstone</td></tr>
<tr><td>Plateau Beds Fm.</td></tr>
<tr><td rowspan="3">Lower</td><td>Brownstones Fm.</td><td rowspan="2">Cosheston Subgroup</td><td rowspan="4">Daugleddau Group
(Lower Old Red Sandstone)</td></tr>
<tr><td>Senni Fm.</td></tr>
<tr><td>St Maughan's Fm.</td><td rowspan="2">Milford Haven Subgroup</td></tr>
<tr><td colspan="2" rowspan="2">Silurian</td><td>Raglan Mudstone Fm.</td></tr>
<tr><td colspan="4">Marine Silurian and older rocks</td></tr>
</table>