The importance of water in aeolian systems; an example from the Sherwood Sandstone of the West Midlands

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The preserved sedimentary expression within dry-land environments was traditionally thought to be the product of either extensive ephemeral (short-lived) fluvial sedimentation or dominated by windblown migrating dune-forms. However, within the last few decades increasing evidence has shown that few dry-land environments remain solely the remit of either aeolian or fluvial process but commonly a mix of both. A number of interactions between these depositional mediums are increasingly being identified within dry-land environments and these have been shown to occur on a variety of scales, as either symbiotic or competitive in nature. Examples of the interactions between fluvial and aeolian facies are observed within the Triassic aged Sherwood Sandstone Group, of western and central parts of England (in and around the Cheshire Basin). On a national scale the Sherwood Sandstone is primarily of fluvial affinity, with its source situated in modern-day north France. The fluvial system of the Sherwood Sandstone Group flowed in a northerly direction across southern and central England from northern France, covering large portions of the Triassic land surface in eastern and western England (the Midlands) and infilling numerous different basins (Fig. 1). Where the fluvial system entered the Cheshire Basin in western England it interacted with a contemporaneous aeolian dune-field, leading to a number of different styles of system interaction.

Rationale

An improved understanding of the range of aeolian-fluvial interactions within dry-land systems and how these processes impact the resultant sedimentary architecture has applied considerations. Firstly, it enables the development of predictive models with which better to account for the palaeoenvironmental significance of the geological record. Secondly, it is important for the development of models that predict sand-body connectivity and heterogeneity, concepts important in the search for, and development of, economic reserves of oil, gas, minerals, water, and carbon capture and storage. This is important in the context of the Sherwood Sandstone Group due to a number of applied fluid flow considerations:

- The Sherwood Sandstone is designated as a principal aquifer in the UK, providing the main source of groundwater for significant parts of the Midlands and northern England (Allen *et al.* 1997; Wakefield *et al.* 2015);
- The group is a hydrocarbon (gas) reservoir in the offshore East Irish Sea Basin (Meadows and Beach 1993a);
- Lateral equivalents of the Sherwood Sandstone in the North Sea are productive (Gray 2014);
- Its spatial setting in the subsurface, often juxtaposed with Carboniferous Coal Measures strata, and also forming rockhead under major conurbations, has resulted in a contamination legacy associated with past industrial use (Bouch *et al.* 2006); Hough *et al.* 2003);
- The pore-space within the Sherwood Sandstone is a potential economic resource, both in terms of extraction of pore-fluids (groundwater and hydrocarbons), and the re-use of pore-space as a potential CO_2 store, a source of shallow geothermal energy, and as a host for compressed air energy storage (Evans *et al.* 2009; Evans and Chadwick 2009).

1 Aeolian Bedforms

The ability of fluvial waters to penetrate within aeolian dune-fields (like the example of the Sherwood Sandstone in the Cheshire Basin) is governed primarily by the arrangement and geometries of the present sand dunes (dune-forms). The presence of aeolian dune-forms, by virtue of their relief, act as barriers and guides to flowing water in the dune-field. This is despite the fact that it has long been recorded that some more extreme incursive water events can have sufficient vigour and duration to cut through and remove some dune-forms (Bullard and McTainsh 2003; Langford 1989; Mountney 2006b). Within modern dryland systems this dune dissection or 'dune breaching' interaction (Fig. 2) is more often associated with repeated gradual erosion of dune-forms over a period of time by separate discrete flood events. The timing of such flood events would have to be sufficently spatially constrained to prevent the aeolian system from rebuilding and 'healing' the damaged dune-forms. Despite examples of sand dune breaching from modern and ancient systems, the ability of water to occupy parts of the aeolian system is still primarily governed by the aeolian dunes. As such, factors controlling the orientation, size, shape, wavelength and migration speeds of aeolian bed-forms, and thus the low-lying inter-dunes, are all important in understanding the resultant and potential interactions that can occur. The following section provides an overview of some of the interaction types identified within the Sherwood Sandstone Group.

2 Inter-dune flooding

Description Thin (up to 1m, commonly <0.6m), red-brown very homogenous, structureless, fine-medium grained sandstones confined by highly homogenous, white-yellow, cross-bedded sandstones. In sections parallel to the palaeowind direction, these elements exhibit a broadly horizontal tabular geometry that extends, where outcrop allows, for 100s of metres. The lower bounding surface of these elements is sharp, irregular and commonly very slightly erosively based. The upper bounding surface is also sharp forming as broad near-horizontal straight surfaces with some minor local-scale irregularity. The upper boundary also sometimes exhibits a stacked onlap relationship (feathered) with the above cross-bedded sandstone unit. In sections perpendicular to palaeowind direction these elements have a broadly lensoidal shape, where they have lateral extents of 10s of metres, though they often occupy the same stratigraphic horizon as other such lenses. Internally these elements are frequently comprised of massive red-brown sandstones, with some examples containing small pebble sized clasts of smeared mudstone. Sometimes rare thin lenses of white-yellow sandstone, only a few grains thick, are observed. These white-yellow lenses can extend up to 200mm laterally and are orientated as horizontal to near-horizontal planes.

Interpretation This element is interpreted as representing an open inter-dune corridor along which water flowed episodically (Kocurek 1981; Lancaster and Teller 1988; Mountney and Thompson 2002). Smeared mud clasts represent rip-up clasts of a more local origin. The structureless nature of the element, the sharp erosive lower boundary and sharp upper boundary suggest rapid deposition with a relatively abrupt cessation. The presence of small mudstone pebbles suggests a sub-aqueous, rather than subaerial, depositional medium. The absence of observed indicators of 'drying' suggests rapid water loss from a 'short-lived event', which prevented the generation of such structures. Indeed the sharp upper bounding surface to this element also suggests abrupt cessation of deposition, supporting the notation of a rapid loss of water (Ahlbrandt and Fryberger, 1981).

Observed instance of a feathered upper bounding surface indicates coeval flooding of the inter-dune with aeolian dune migration. The inclusion of millimetre scale white-yellow lenses is interpreted as minor reworking of the underlying sand dune facies during flooding.

3 Inter-dune lakes: dune damming

Description Comprising up to 1.5m thick lenses that can have lateral extents both parallel and perpendicular to palaeowind direction of 10s of metres. These lenses are situated within and compartmentalised by white-yellow cross-bedded sandstones. Lower and upper bounding surfaces are sharp with the upper surface commonly exhibiting polygonal cracks that are frequently infill by the overlying white-yellow sandstone. Internally, this element comprises numerous facies types, including laminated sandstone, laminated siltstone and mudstone, and rippled sandstone. Ripple-forms within this element are symmetric and have crest heights up to 20mm with observed wavelengths from 50mm to 150mm. Crestline orientations are variable, but have a modal orientation perpendicular with palaeowind directions.

Interpretation This element is interpreted as a dune-dammed lake or pond (Fig. 2). Observed examples of symmetric ripples are indicative of wind-agitation on standing bodies of water. The presence of polygonal cracks (desiccation cracks) indicate episodic drying of the standing water. Examples of the desiccation cracks at the lateral margins of this element result from the lake or pond margins being most sensitive to changes in the water level. The presence of ponded water is likely the result of a dune-form configuration that was at least partially enclosing the inter-dune, preventing water escape by further flows.

4 Accessory flooding: Watertable rise

Description Thin lensoidal shaped elements with lateral extents up to 10m in palaeowind parallel and perpendicular sections. The lower bounding surface of these lenses is often diffuse and relatively hard to define, as it is compositionally indistinct from the underlying facies types from which it is clearly reworked. As such, the disruption or absence of the original sedimentary structure (cross-bedding) commonly defines the base of this element. The upper bounding surface is frequently undulose or feathered with the overlying white-yellow cross-bedded sandstones. Internally this element contains white-yellow sandstones that exhibit wind-ripples, horizontal lamination, deformation (contortion) and asymmetrical ripples. Vertical calcrete nodules are also sometimes observed in the upper portions of the element.

Interpretation This element is interpreted as an accessory flooded wet inter-dune that was fully enclosed by aeolian sand dunes (Fig. 2). The presence of water is indicated by: rare examples of asymmetric rippleforms, interpreted as wind-agitated subaqueous ripples; deformation structures associated with dewatering, likely resulting from compression by the overlying migratory sand dune (Mountney, 2006); and plant colonisation evidenced by small rooting (vertical calcrete nodules).

Unlike dune dammed inter-dune ponds and lakes, this element has a complete absence of any fluvial facies types and instead comprise facies from aeolian origin or reworked aeolian facies only. This absence of fluvial facies suggests that the inter-dune was completely isolated from the fluvial system. The water present within the dune-field could have been sourced either by a watertable rise above the level of the interdune surface, or as

infilling by rainfall within the system. A watertable rise is the preferred interpretation, as the volume of water and duration of rainfall needed to sustain a standing body of water for a significant period of time (to allow plant colonisation or the formation of wind-agitated ripples) likely precludes rainfall as the mechanism.
The interpretation of the inter-dune being completely enclosed, necessitates that the surrounding (bounding) sand dunes had sinuous crestlines. It also suggests that the bounding sand dunes to the inter-dune were likely relatively closely spaced (short-wave lengths) and were most probably arranged in an out-of-phase configuration.

Conclusion

Deposition of aeolian and fluvial systems in dry-land environments can lead to a number of different interactions types. Study on the mixed aeolian-fluvial Sherwood Sandstone Group of the Cheshire Basin, reveals three distinct types of interaction: (i) inter-dune flooding, (ii) dune damming and, (iii) accessory flooding. These interactions form as a result of aeolian sedimentation (sand dunes and inter-dunes) occurring coevally with sources of water from fluvial systems, watertable rises or rainfall. An understanding of these interactions is important as they can add local- to regional-scale heterogeneity, which might be impactful on fluid flow with the preserved sedimentary deposits.

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