

Supercritical-flow structures on a Late Carboniferous delta front: Sedimentologic and paleoclimatic significance

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ABSTRACT

Deposits of fluvial systems in highly seasonal tropical climates possess unique architectural and facies characters owing to a flood-prone regime alternating with lengthy periods of ineffective discharge. Distally linked deltaic successions should also feature distinctive attributes, with great potential to preserve the stratigraphic evidence of exceptional discharge events. We describe Late Carboniferous delta-front, valley-confined sandstones from the Pennine Basin (UK), originally deposited at paleoequatorial latitudes during final assembly of the Pangean megacontinent and characterized by giant sedimentary structures with repetitively sigmoidal geometry. Facies traits indicate geologically instantaneous deposition of a large sediment volume from a density current at sustained supercritical-flow conditions, leading to aggradation of cyclic steps, recently identified bedforms developing in high-energy flows and of which this is the first complete outcrop example. The lack of unconformable erosional surfaces and absence of different associated facies point to a single aggradational event during which the structures attained dimensions comparable to those indicated by seismic data sets from which they are remotely detected on modern seafloors. Cyclic-step formation in a deltaic setting suggests that Pangean megamonsoons could have triggered hydrologic events capable of imprinting sedimentologic signatures on shallow-marine deposits.

INTRODUCTION

Fluvial systems in tropical monsoonal regions of pronounced seasonality are subject to high discharges and occasional catastrophic floods concentrated in months of intense precipitation, alternating with lengthy times of relative hydrological inactivity (Kale, 2008; Fielding et al., 2009). Recent studies show that deposits of such rivers feature attributes recognizable in ancient successions, including complex scoured architectures, abundant sedimentary structures related to supercritical flows, and coarse overbank facies (Fielding et al., 2009). Deltas fed by such flood-prone systems should have great potential to preserve sedimentological signatures of major discharge events.

Recent advances on sediment-bed configurations and associated structures under unidirectional supercritical flows have led to the identification of cyclic steps, bedforms developed at particularly high Froude numbers (Taki and Parker, 2005; Kostic et al., 2010; Cartigny et al., 2014). Described at large scales from geophysical data on modern seafloors (Covault et al., 2014), cyclic steps were long unrecognized as primary bed configurations and generically denoted as “sediment waves” (e.g., Wynn et al., 2000). Corresponding sedimentary structures have been sparsely observed only in partial outcrop examples (Lang and Winsemann, 2013; Postma et al., 2014), due to limited preservation during high-energy events and reworking by waning flow stages. We describe Late Carboniferous deltaic sandstones from the Pennine Basin (UK) showing a unique stratal architecture with giant sedimentary structures interpreted as the first outcrop record of a fully preserved train of cyclic steps accreted under sus-

tained supercritical regime and sediment supply. “Megamonsoonal” seasonality (Parrish, 1993) affected the paleotropical Pennine Basin during the early assemblage of Pangea, forming the climate framework for the hydrological processes that originated these anomalous structures.

GEOLOGICAL AND PALEOCLIMATIC SETTING

The Central Pennine Basin (UK) was located on the eastern Laurasian margin at northern subequatorial latitudes (Fig. DR1 in the GSA Data Repository¹; Davies, 2008; McKerrow and Scotese, 1990) during Late Carboniferous final assemblage of Pangea. The studied outcrops span the northern face of the Derby Delph Quarry (near Huddersfield, West Yorkshire; Fig. 1) and the lower banks of the adjacent Booth Wood Reservoir, and belong to deltaic deposits of the Lower Kinderscout Grit (Hebden Formation) within the Millstone Grit Group (Fig. DR2). The latter comprises coarse sandstones and mudstones that filled deep backarc sub-basins a few hundred kilometers north of the Hercynian orogen during post-rift subsidence (Collinson, 1988). Fluvio-deltaic systems prograded into each sub-basin in a south to southwest direction, supplied by a large drainage to the north (Collinson, 1988; Davies, 2008) and feeding turbiditic successions that filled the local basement topography. The “turbidite-fronted deltas” of the Millstone Grit (Collinson, 1988; Hampson, 1997) were analogous to shelf-edge deltas in their steep subaqueous fronts and efficient sediment transfer basinward. In the Huddersfield sub-basin, the Derby Delph Quarry exposes early Bashkirian, proximal deltaic clinoforms belonging to an early-transgressive incised-valley fill, overlain by fluvial “topset” deposits outcropping ~100 m to the north, and correlative down dip to turbidite strata (McCabe, 1977; Hampson, 1997; Waters and Condon, 2012).

Climate was subhumid to humid in this subequatorial region, and monsoonal conditions were established since the early Carboniferous (Falcon-Lang, 1999), their intensity gradually increasing as major landmasses merged into a configuration that enhanced seasonal patterns of atmospheric

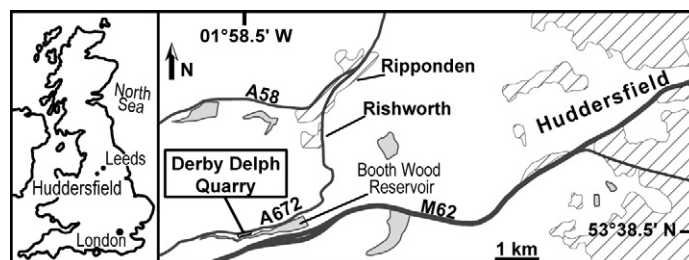


Figure 1. Derby Delph Quarry is located directly north of Booth Wood Reservoir, near Huddersfield (West Yorkshire, UK); diagonal patterns outline urbanized areas.

¹GSA Data Repository item 2015251, supplementary figures (paleogeographic location, lithostratigraphic framework, Booth Wood Reservoir outcrop, and cyclic-step dynamics), 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.

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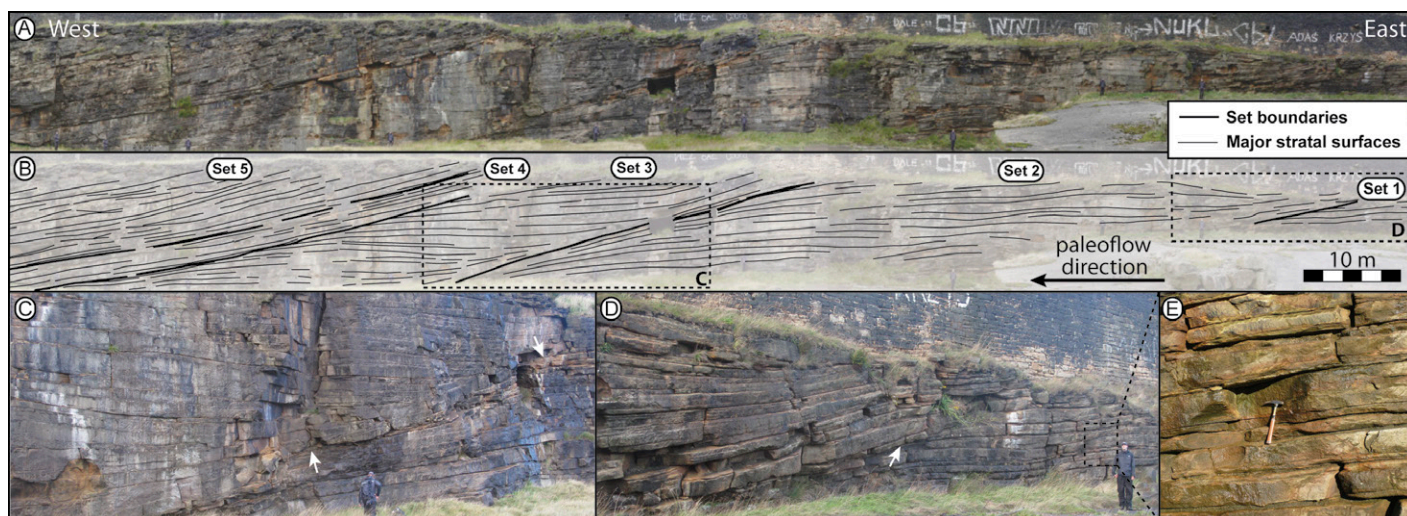


Figure 2. A,B: Panoramic view (A) and schematic interpretation (B) of northern quarry face, offering flow-parallel section of sedimentary structures. C: Bounding surface (white arrows) between sets 3 and 4 (see B for location). D: Transition between sets 1 and 2 (white arrow; see B for location). E: Detail of set 1 (inset in D): massive, coarse sandstones with interbedded finer sandstone (hammer is 32 cm long).

circulation, owing to the contrast in thermal inertia between the Pangean protocontinent and surrounding oceans (Parrish, 1993). The concurrent evolution of late Paleozoic glaciation in the Southern Hemisphere forced global climate to vary at orbital time scales (10^4 – 5 yr), in phase with glacioeustasy. Monsoonal intensity was affected by orbital cycles, being directly controlled by hemispheric insolation and by the co-varying atmospheric $p\text{CO}_2$ (Horton et al., 2007).

SUPERCritical-FLOW STRUCTURES: INTERPRETATION

The northern quarry face extends for more than 200 m in an ENE-WSW direction with a height of ~13 m (Figs. 2A and 2B). Most of the exposure consists of a peculiar association of large sets of low-angle, sigmoidal sandstone strata bound by steeply dipping erosional discontinuities (Figs. 2A–2D), transitional to steeper subplanar foresets at the western quarry end. An identical architecture is exposed along the lower banks of the Booth Wood Reservoir (Fig. DR3). A quarry face at the western end with perpendicular orientation provides a three-dimensional perspective highlighting foreset dip to the southwest, slightly oblique ($\sim 10^\circ$) to the main face, and consistent with regional paleotransport trends (Collinson, 1988).

Five stratsets are distinguished (Fig. 2) for description and interpretation. Sets 1–3 (Fig. 2) measure several tens of meters in length, dip westward (downcurrent), and consist of conformably stacked sandstone strata displaying a low-amplitude, undulating geometry with a wavelength of 10–15 m. Sets are delimited by distinct boundaries dipping to the west at much steeper angles than individual strata; each boundary truncates underlying sandstones, whereas overlying strata terminate tangentially against it, stacking progressively upcurrent in an eastward direction (Figs. 2A–2D). The majority of strata consist of poorly sorted, medium to very coarse, massive sandstones (Figs. 2E and 3) comprising dispersed granules, pebbles (Fig. 3A), and coalified organic debris (Fig. 3B). Strata are ~20 cm thick on average, with non-erosive or weakly erosive base and laterally continuous up to their terminations at set boundaries. These coarse sandstones define the general architecture, but are commonly intercalated by thinner, crudely layered strata of finer, better-sorted sandstone (Figs. 2E and 3A), conformable to the overall set geometry, locally presenting a broadly undulating internal geometry and rare centimetric laminasets steeply dipping upcurrent (eastward) within small scours. Cross-laminated and cross-bedded facies are otherwise absent. The only change in architecture is represented by tabular clinoforms of set 5 at the western quarry end (Figs. 2A and 2B), denoting subaqueous progradation. A transitional set 4 consists of gently

undulating, massive sandstones dipping at higher angle compared to sets 1–3 (Fig. 2A) and retrogressively onlapping the boundary with set 3.

Apart from set boundaries, unconformable erosive surfaces were not observed. The absence of mud-rich units, bioturbation, and deformed horizons indicates that the sediment-water interface was subject to uninterrupted aggradation over the whole stratigraphic interval. Missing evidence for erosion and reworking under variable flow regimes stands in marked contrast to the lateral and vertical heterogeneity typical of deltaic and shallow-marine successions.

In view of the geological setting, the most likely interpretation for rapid aggradation of such a large sediment volume and for the stratal architecture is a high-magnitude fluvial flood with exceptional sediment load, plunging seaward of the river mouth as supercritical hyperpycnal flow (Mulder et al., 2003). The architecture and proximal-to-distal stacking of strata sets are consistent with experimental insights on mobile-bed configurations under supercritical sediment-laden currents (Cartigny et al., 2014; Covault et al., 2014). The extensive, westward-dipping set boundaries onlapped by massive sandstones are interpreted as erosion immediately followed by deposition at the transition from supercritical to subcritical flow in bedform troughs. Subcritical to transcritical flow over bedform stoss sides succeeded downstream by supercritical flow along steeper lee sides constitutes the typical pattern of unidirectional currents over cyclic steps (Fig. DR4), asymmetrical bedforms which accrete and migrate upcurrent under periodic flow instabilities at high Froude num-

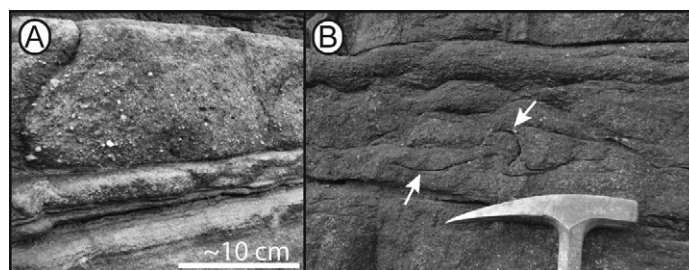


Figure 3. A: Massive, poorly sorted, gravelly coarse sandstones underlain by crudely laminated, finer sandstones. B: Chaotic attitude of coalified plant fragments (white arrows), originally soft at deposition, indicates burial by rapidly aggrading sediment-water interface (hammer head is 18 cm long).

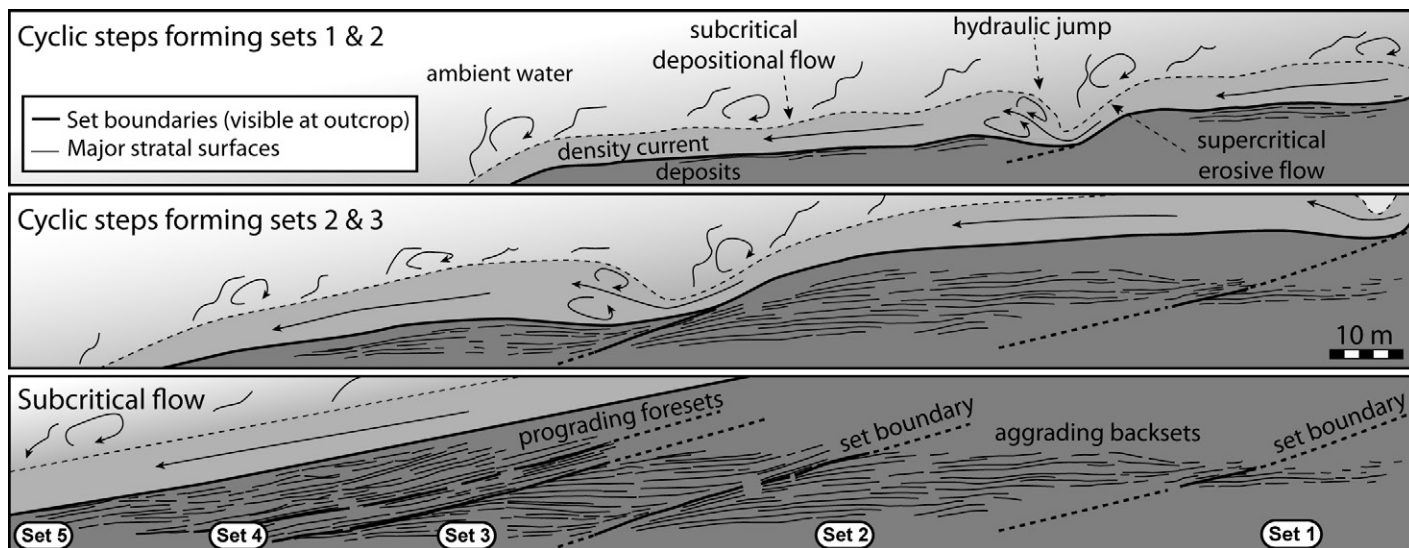


Figure 4. From top to bottom, this simplified process model illustrates main depositional stages (see text for details).

bers (Kostic et al., 2010; Cartigny et al., 2014). The transition between the two flow regimes at bedform troughs is represented by a hydraulic jump, where abrupt reduction in flow velocity and increase in flow depth trigger deposition, reflected by the retrogressive onlap of sandstone strata onto set boundaries. With moderate sediment supply and reduced aggradation rates, these processes produce asymmetric structures consisting mostly of stacked stoss laminae. However, protracted, exceptional sediment loads can force lee-side preservation, as observed here. Strata within set 4 represent a retrograding hydraulic jump, indicating distal transition to subcritical flow (Fig. 4).

High rates of sediment supply and aggradation explain the dominance of poorly sorted, massive sandstones, reflecting dampened turbulence and rapid deposition from basal concentrated layers of the density current (Cantero et al., 2011). Scattered organic debris was entrained on alluvial plains as the flood wave approached the coast (Mulder et al., 2003). Finer sandstone interbeds (Fig. 3A) with wavy laminae and rare laminasets accreting countercurrent relate, respectively, to temporarily reduced aggradation under the unsteady hypopycnal current (Best et al., 2005) and to local inversion of the flow field close to hydraulic jumps migrating upstream. Temporary decreases in Froude number may have led to superposed antidunes (e.g., set 2; Kostic, 2014). The depositional event may have lasted up to several days, as currently observed where exceptional floods generate long-lived underflows at river mouths (Mulder et al., 2003).

In this classical study area for Paleozoic geology, previous workers noticed the anomalous scale and configuration of these sedimentary structures, interpreted as dunes washed out at flood peak in delta distributary channels (McCabe, 1977) or as giant cross strata filling migrating fluvial confluences (Hampson, 1997). In light of recent advances on upper-flow-regime bedforms, the mechanism proposed here better fits the general architecture and facies homogeneity of the outcrop. Preservation of such large, organized strata sets would have been unlikely on a subaerial delta plain, where minimal accommodation and frequent reworking by active channels would have generated a more heterogeneous facies association.

MONSOONAL FLOOD ON TROPICAL PANGAEA

The Derby Delph Quarry offers the first outcrop example of a fully preserved train of large cyclic steps. Similar sets of cyclic steps so far were recognized only through seismic evidence as products of long-lived turbidity currents (Wynn et al., 2000; Covault et al., 2014). In flood-dominated (paleo)tropical fluvial systems, conditions favorable to their development can be attained at discharge peaks in the wet season, but recessional flow

stages typically erode or rework the resulting deposits. However, excess accommodation on subaqueous delta fronts may allow the preservation of facies and architectures related to maximum discharge.

Neogene to Quaternary records of tropical fluvio-deltaic and offshore systems point to (paleo)monsoon intensity as a fundamental control on sediment yield from source areas and on transport efficiency basinward (Goodbred and Kuehl, 2000). Alternate seasons with markedly opposite hydrological balance result in landscape instability coupled with severe floods carrying large volumes of terrigenous material (Kale, 2008). This combination of high discharge and considerable sediment load is inferred for deposition of the Derby Delph sandstones, which represent delta-front progradation within an incised-valley fill during an interglacial sea-level rise (Hampson, 1997), corresponding to strengthened monsoonal circulation during the late Paleozoic ice age (Horton et al., 2012).

The Pennine Basin was shifting northward across subequatorial latitudes during early Late Carboniferous suturing of Laurussia with Gondwana. Growing seasonality due to Pangean continentality (Davies, 2008) was accompanied by increasingly humid conditions, enhanced by Gondwanan ice masses that stabilized the intertropical convergence toward the Northern Hemisphere. At low latitudes, climate seasonality was dampened during relatively humid glacial phases; conversely, drier but highly seasonal interglacials resulted in intensified Pangean monsoons (Horton et al., 2012), as recognized also in Pleistocene paleoclimate records (Rossignol-Strick, 1983). Strong glacioclimatic fluctuations affected the Pennine Basin during deposition of the Lower Kinderscout Grit (Waters and Condon, 2012) since a widespread expansion of glaciation centers occurred in the early Bashkirian (Fielding et al., 2008).

Monsoonal regions are subject to considerable precipitation and powerful floods lasting from days to weeks. The distinctive stratal architecture at Derby Delph indicates geologically instantaneous deposition of a great sediment volume during a prolonged flood of exceptional discharge, sustaining continuous aggradation of giant cyclic steps. Production of this distinctive macrofacies in a shallow-marine setting during a Late Carboniferous interglacial stage of enhanced seasonality points to a strong connection with the monsoonal climate of early Pangea, and shows that identification of anomalously large supercritical-flow structures in the rock record forms a criterion to recognize extreme hydrologic events.

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