Nature and Origin of the Systematic Stacking Pattern of Matrix-Rich and Associated Matrix-Poor Strata in Two Tectonically Different Deep-Marine Turbidite Systems.

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Summary

Exceptional exposure of matrix-rich and associated matrix-poor sandstones in the Neoproterozoic Windermere turbidite system (British Columbia, Canada) and the Ordovician Cloridorme Formation (Quebec, Canada) provide an unparalleled opportunity to document both lateral and vertical changes in lithology. In both study areas, these strata form a horizontal depositional continuum, which from proximal to distal, consists of matrix-poor sandstone to muddy sandstone to bipartite bed and then sandy mudstone over a distance of a few to several 100s m, which then is draped everywhere by a thin-bedded turbidite and/or silty mudstone cap. Vertically, similar facies preferentially overlie one another and form packages 2-9 beds thick. Additionally, within an individual package, beds transition to more distal facies and ultimately pinch out at approximately the same along-strike position. Collectively, these consistent vertical and lateral changes in lithology suggest regularity in the spatial and temporal patterns of sedimentation, which here is interpreted to be a consequence of particle settling in a rapidly, but systematically evolving negligibly-sheared, sand-mud suspension associated with avulsion-related flows. At the package scale, the reluctance of similar packages to stack vertically, but the preferential vertical juxtaposition of dissimilar packages, indicates compensational stacking and the episodic diversion followed by temporary stabilization of the avulsion jet to a hydraulically more favorable position on the seabed.

Introduction

The description, classification, and origin of deep-marine matrix-rich sandstones (i.e. sandstone with significant (> 20%) clay and silt matrix) have been debated since the 18th century when the term greywacke was introduced into the geological literature as 'grauwache' by Lasius (1789, in Huckenholz 1963). Sedimentologists have generally attempted to either define them based on their texture and/or composition (see review in Klein 1963), or origin of the matrix (detrital vs. diagenetic) (see review in Cummins 1962). However, in the last decade, it has been increasingly recognized that there exists a variety of matrix-rich strata that are unlike classical turbidites or debrites and should be examined and interpreted based on their formative physical mechanisms and associated depositional environments. Currently, deep-marine matrix-rich beds are categorized as slurry beds (Lowe and Guy 2000), hybrid-event beds (Haughton et al. 2009), transitional flow deposits (Kane and Ponten 2012), and matrix-rich sandstones (Terlaky and Arnott 2014).

In addition to the plethora of terms used to describe these strata, are the many proposed physical mechanisms responsible for their deposition, including: hybrid flows consisting of at least two discrete and mechanistically different parts (Haughton et al. 2009), longitudinal flow transformation (Kane and Ponten 2012), vertical stratification effects and turbulence suppression (see review in Talling 2013; discussion in Kane et al. 2017), and particle settling in mixed mud-sand suspensions (Angus et al. 2019). Part of this uncertainty may be because much of the current geological literature, with exception of a small number of studies (e.g., Talling et al. 2004; Terlaky and Arnott 2014, Fonnesu et al. 2015; Angus et al. 2019), is based on macroscopic observations in drill core and discontinuous outcrops that fail to capture details of vertical and lateral variability in lithofacies.

Exceptional exposure of matrix-rich and associated matrix-poor strata in the Neoproterozoic Windermere turbidite system (British Columbia, Canada) and the Ordovician Cloridorme Formation (Quebec, Canada) permit centimeter- to millimeter-scale observations to be carried out over distances of 10s of meters vertically, but more significantly, 100s of meters laterally. This, then, provides an unparalleled opportunity to accurately investigate the compositional (matrix volume) and textural (grain-size distribution) characteristics of matrix-rich and associated matrix-poor sandstones, both vertically and laterally, and ultimately, assess the spatial and temporal evolution of these strata. In addition to being of academic interest, these mud-rich strata exhibit poor reservoir quality (i.e. porosity and permeability) which makes understanding their depositional origin, architecture, and stratigraphic distribution essential for more accurately modelling (hydrocarbon) reservoir architecture and performance.

Lithological and Stratigraphic Characteristics

Based on matrix content, four lithofacies (Figure 1) are recognized in both study areas: thick- to medium-bedded, fine- to coarse-grained, coarse-tail graded matrix-poor sandstone (MPS) (<20% matrix); medium- to thin-bedded, fine- to coarse-grained, massive to coarse-tail graded muddy sandstone (MS) (20-50% matrix); medium- to thin-bedded, fine- to coarse-grained, massive to coarse-tail graded bipartite bed (Bb) with a basal sandy (20-60% matrix) part overlain sharply by a planar- to irregular-based muddier portion (40-80% matrix); and medium- to thin-bedded, fine- to coarse-grained, massive sandy mudstone (SM) (50-80% matrix).

These facies form an along-strike depositional continuum consisting of MPS to MS to Bb and then SM over 10s to 100s meters (Figure 1). Where preserved, the entire transect is capped by fine- to medium-grained, thin-bedded traction structured sandstone and/or silty mudstone.

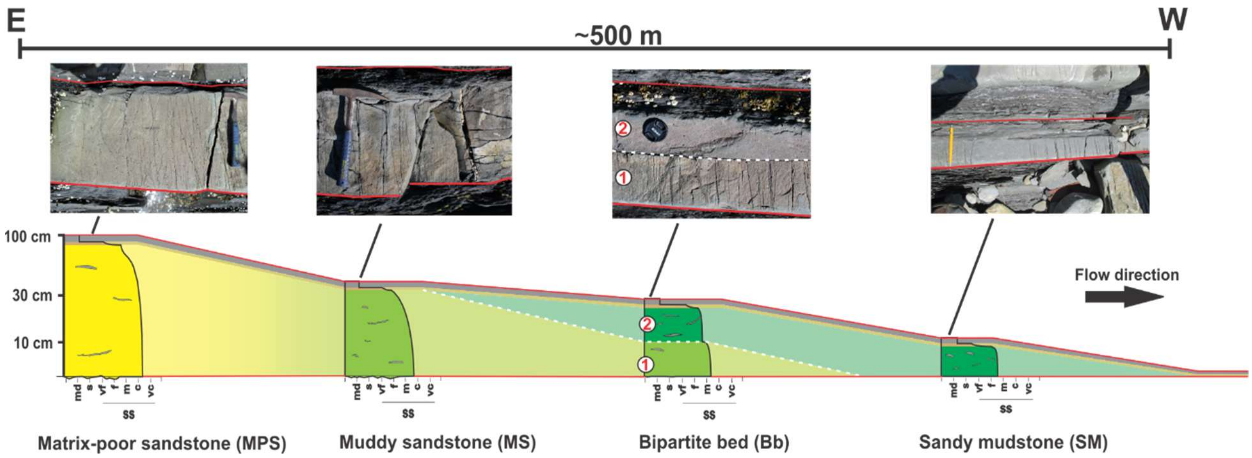

Figure 1. Outcrop photographs and schematic of full lateral facies transect from Matrix-poor Sandstone to Muddy Sandstone to Bipartite bed to Sandy Mudstone in the Cloridorme Formation. A matrix-poor, thin-bedded, traction-structured unit overlain by silty mudstone cap drapes the entire transect. Red lines indicate bed contacts and white dashed lines indicate interface in a bipartite bed. Note that this transect represents a single bed.

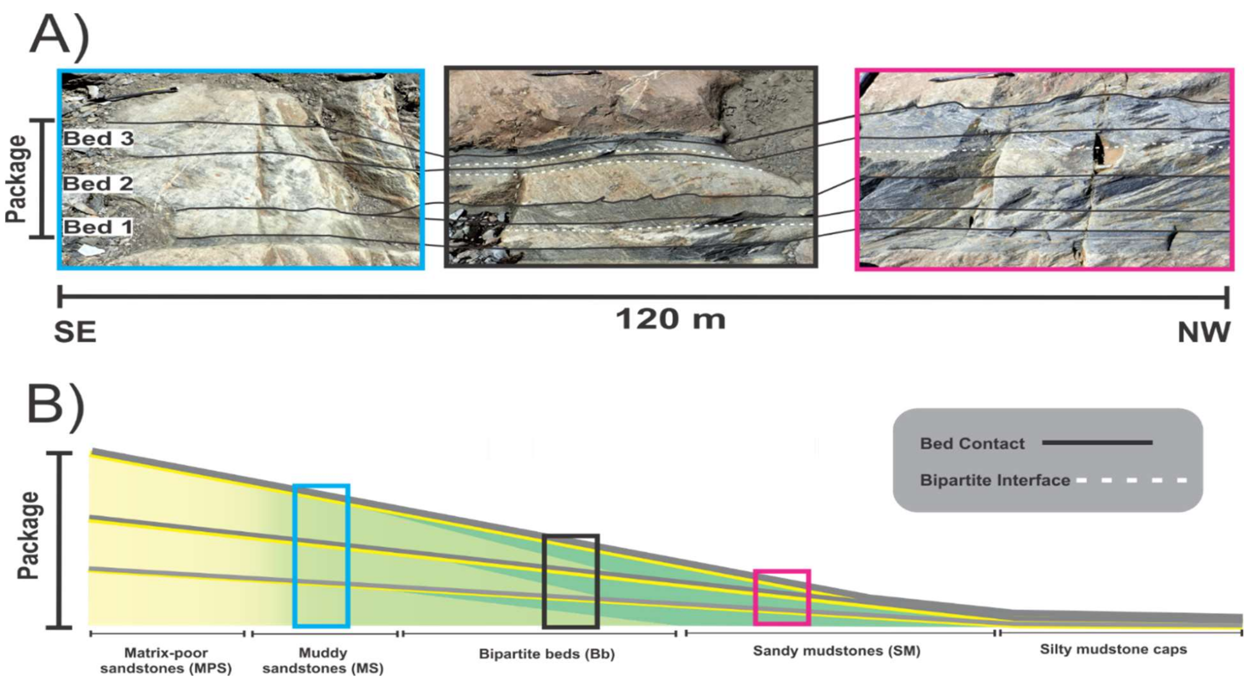

Figure 2. A) Correlated outcrop photographs of an individual package composed of three lithologically similar beds that change from more proximal facies (left) to more distal facies (right) at about the same position laterally. B) Schematic showing the vertical stacking pattern of the lateral facies succession (not to scale). Coloured rectangles refer to the representative photos above.

Based on field observations, and verified statistically, similar facies typically succeed one another vertically and form packages 2 to 9 beds thick (Figure 2); all other transitions are less than expected or random. Additionally, within a discrete package, beds transition to more distal facies and ultimately pinch out at approximately the same along-strike position (Figure 2). Lastly, within an individual package, the grain size decreases stratigraphically upward. On a larger scale (package scale), similar packages are statistically less likely (than random) to overlie one another, whereas dissimilar packages are statistically more likely to stack.

Depositional Model

Based on field observations in this study, and earlier reported by Terlaky & Arnott (2014) and Angus et al. (2019), matrix-rich and associated matrix-poor sandstones typically underlie large-scale stratal elements, such as terminal splays, distributary channels, and slope channels, which suggest that deposition of matrix-rich strata are related to local activation of the system, quite possibly related to avulsion of an up-dip channel (Terlaky & Arnott 2014). Avulsion forms an unconfined plane-wall jet that scoured the mud-rich seafloor in the interchannel area, enriching it with fine sand to clay particles and low-density clay clasts (Terlaky & Arnott 2014). Along the margins and distal part of the avulsion jet, the newly sourced and now suspended fine-grained sediment caused turbulent kinetic energy (TKE) to be rapidly dissipated as flow momentum was transferred to particle motion in order to maintain the particle suspension (Angus et al. 2019; Bennett et al. 2013). This dramatic reduction in TKE caused the now completely momentum- and buoyancy-driven sediment suspension to immediately collapse and deposit a systematic succession of lithofacies consisting of MPS to MS to Bb and then SM over a distance of 10s to several 100s meters. At all times the suspension was overlain by a low-density turbidity current that reworked the underlying deposit. Ultimately, any remaining suspended silt and clay formed a near-bed fluid mud layer that rapidly developed strength and deposited a silty mudstone cap.

Vertically, the deposition of similar facies within a package and their consistent lateral change in lithology suggest regularity in the spatial and temporal patterns of sedimentation, which here is interpreted to be a consequence of particle settling in a rapidly, but systematically evolving negligibly-sheared, sand-mud suspension associated with avulsion-related flows that are generated by multiple pulses of a single turbidity current. Importantly, the time between the successive pulses must be of sufficient duration to allow for the emplacement of the traction structured sandstone and overlying mud cap.

At the package scale, dissimilar rather than similar packages show a statistically significant preference to stack vertically. Considering that each package represents deposition in different parts of the along-strike facies transect, these results indicate the abrupt spatial displacement of the facies succession, followed by temporary stabilization of the flow and sedimentation conditions. This is interpreted to be the result of compensational stacking and the episodic diversion followed by temporary stabilization of the avulsion jet in a hydraulically more favorable position.

Conclusion

In both study areas, a consistent lateral succession of facies, which from proximal to distal, consists of MPS to MS to Bb to SM, collectively overlain by a thin-bedded turbidite and/or silty mudstone cap is observed over a distance of 10s to 100s meters. These changes are interpreted to reflect particle settling in a negligibly-sheared, sand-mud suspension along the margins and distal part of an avulsion jet. Vertically, similar facies tend to preferentially stack and build up 2-9 bed-thick packages implying that beds within a single package were deposited from successive flows of similar hydraulic and compositional character. At the package scale, similar packages are less likely to stack than predicted in a random distribution, whereas dissimilar packages are more likely to vertically stack. This stacking pattern suggests compensational stacking and the episodic diversion followed by temporary stabilization of the avulsion jet in a hydraulically more favorable position on the seabed.

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