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Spatial, Temporal and Physical Origin of Matrix-Poor to Matrix-Rich Sandstones on a Deep-Marine Slope, Isaac Formation, Neoproterzoic, Windermere Supergroup, British Columbia, Canada

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Summary

At the Castle Creek study area a remarkably well exposed section in the Isaac Formation, Windermere Supergroup, was measured to document potential lateral and vertical changes in facies. Here, a consistent lateral succession of facies was observed consisting of matrix-poor sandstone to clayey sandstone to bipartite bed to sandy claystone, collectively overlain by a thin-bedded turbidite and mudstone cap. These changes are interpreted to reflect particle settling in a negligibly-sheared sand-mud suspension following detachment from the margins of an avulsion jet. Vertically, similar facies stack to form packages 2-7 beds thick implying temporary stabilization of jet-margin dynamics. At a larger scale facies stack to form three stratal assemblages. SA-1: intercalated matrix-rich and matrix-poor strata and SA-2: matrix-rich strata stack vertically and laterally but then are sharply overlain everywhere by classical turbidites of SA-3, indicating a dramatic change from deposition immediately downflow of an avulsion node to conventional levee deposition.

Introduction

Since the pioneering of Kuenen and Migliorini (1950) on the origin of graded bedding and description of the stratigraphic makeup of complete and partial turbidites (Bouma 1962; R. Lowe 1982), much is known about the sand-rich part of the deep-marine sedimentary record. Less well known are deep-marine sandstones rich in detrital fine-grained (i.e. mud) matrix, which include strata termed argillaceous sandstones (Enos 1969), slurry beds (Lowe and Guy 2000), linked debrites (Haughton, Barker, and McCaffrey 2003), hybrid event beds (Haughton et al. 2009), co-genetic turbidite-debrites (Talling et al. 2004), transitional flow deposits (Kane and Pontén 2012), and matrix-rich sandstones (Terlaky and Arnott 2014). In addition to the plethora of terms to describe these strata, are the many proposed physical mechanisms responsible for their deposition. In part, some of this uncertainty is because many of the examples are described from core or from discontinuous and generally poorly exposed outcrops, and as such details of any vertical, but especially lateral variability, is generally unknown. Exceptional exposures of matrix-rich sandstones at the Castle Creek study area permit centimeter- to millimeter-scale observations to be carried out over distances of 10s of meters vertically, but more significantly, 100's of meters laterally. This, then, provides an unparalleled opportunity to accurately investigate the textural, lithological, and mineralogical composition of matrix-rich sandstone deposits both vertically and laterally, and ultimately details of their vertical stacking architecture. In addition to being of academic interest, these mud-rich strata exhibit poor reservoir quality (i.e. porosity and permeability) which makes understanding their origin, and therefore prediction of spatial distribution, essential for more accurately modelling (hydrocarbon) reservoir architecture and performance.

Lithological and Stratigraphic Characteristics

At the Castle Creek study area a remarkably well-exposed, recently deglaciated, vegetation free, 30m thick by 350m wide section containing both matrix-rich and matrix-poor strata was measured in bed-by-bed detail to document changes in facies and facies association -- note that matrix is considered to consist of silt or finer sediment. Based on these data five facies are recognized (Figure 1): F1A) medium-bedded, scour-based, matrix-poor (<20% matrix), normally graded, structureless sandstone; F1B) medium- to thin-bedded, scour-based to wavy-based, massive, matrix-intermediate (20-50%) structureless clayey sandstone; F2) medium- to thin-bedded, flat-based, matrix-rich (50-70%), massive, structureless sandy-claystone; F3A) thin-bedded, fine sand to silt, traction-structured sandstone; F3B) thin- to thick bedded, flat-based, planar and/or ripple cross-stratified, medium to fine sand sandstone, and F4) massive to graded mudstone. Mudstone intraclasts are common in F1A, F1B, and F2.

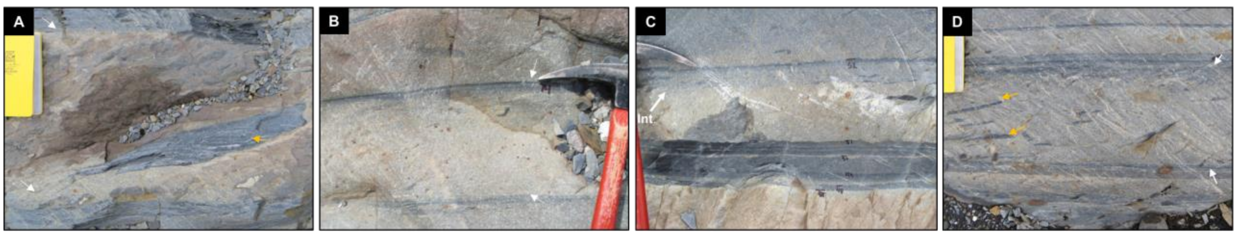

Figure 1. Outcrop photographs of A) Facies F1A) matrix-poor (<20% matrix), structureless sandstone. B) Facies F1B) matrix intermediate (20-50% matrix), structureless clayey sandstone. C) Biparptite bed consisting of a lower clayey sandstone (F1B) sharply overlain by a sandy claystone (F2). D) Facies F2 typically massive, structureless sandy-claystone. Bed contacts are indicated by white arrows. Orange arrows indicate mud clasts.

Laterally these facies exhibit a systematic change from matrix-poor (F1A) to more matrix rich (F2) strata. Specifically, matrix-poor sandstone (F1A) grades laterally into clayey sandstone (F1B). Further laterally, the clayey sandstone becomes sharply overlain by a sandy claystone (F2). Collectively, these two parts, which are separated by a sharp planar surface, form a single bipartite bed (Figure 1.B). Further laterally, the lower clayey sandstone thins and then pinches out, at which point the upper sandy claystone (F2) comprises the entire bed. Nevertheless, further laterally it too thins and then pinches out. Finally, the entire transect is draped by a traction-structured sandstone (F3A) capped by mudstone (F4).

Stratigraphically upward, like facies typically succeed one another and form packages comprising 2 up to 7 beds. Additionally, beds within each package exhibit similar lithology and thickness. At a larger scale (several meters), packages stack vertically to form three distinctive stratal assemblages: SA-1) made up of a single bed or stack of matrix-poor sandstone that is then overlain sharply by 1 to 2 packages of exclusively matrix-rich strata (clayey sandstone, bipartite beds, or sandy claystone) and collectively form dm- to m-thick bedsets that then repeatedly stack to form a 1.5-4.5 m thick assemblage; SA-2 is composed exclusively of matrix-rich packages (clayey sandstone, bipartite beds, and sandy claystone) that build assemblages up to 2.0 m thick; (SA-3) consists of classical (matrix-poor) turbidites that stack to form assemblages 2-6 m thick. Vertically, SA-1 and SA-2 stack and are sharply bounded by successions consisting exclusively of traction-structured turbidites (SA-3). Additionally, SA-1 transitions laterally to more distal facies and then into SA-2 (Figure 2).

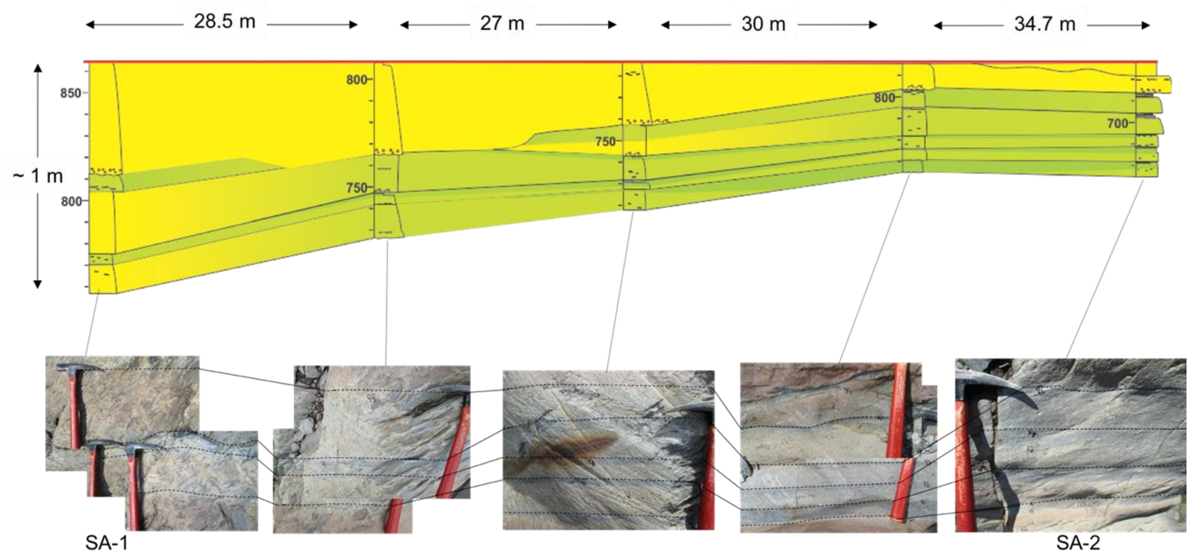

Figure 2. Stratigraphic correlation panel and accompanying outcrop photographs of intercalated matrix-rich and matrix-poor strata (SA-1) transitioning laterally into exclusively matrix-rich strata (SA-2). Note scouring and amalgamation of beds is highest in SA-1. Blacks dashed lines denote bed contacts. In the correlation panel yellow indicates matrix-poor facies, while green denotes matrix-rich facies.

Depositional Model

As suggested earlier by (Terlaky and Arnott 2014) and Angus (2016), deposition of the strata described here are related to vortex shedding from the lateral margins of a turbulent jet related to an upflow channel avulsion. The lateral facies change from matrix-poor (F1A) to matrix-intermediate (F1B) to matrix-rich (F2) strata is interpreted to reflect deposition from a negligibly-sheared, sediment-laden plume that became separated from the main avulsion flow. The now detached, negligibly-sheared suspension advected away from main jet and immediately began to collapse. Initially, the upward component of turbulence was the primary sediment support mechanism, enabling particles to settle according to their fall velocity. However, as the suspension moved further away from the main jet and collapsed toward the bed, hindered settling became increasingly important and eventually became the primary sediment support mechanism. Specifically, the downward (constant) mass flux of settling particles resulted in the upward displacement of ambient fluid and easily suspended fine-grained sediment and low-density mud clasts. The buildup of this fine sediment in the upper part of the collapsing suspension formed the sharply defined sandy clay(stone) layer in the upper part of a bipartite bed. Eventually the basal part of the suspension became completely depleted of settling sediment through deposition as the upper part continually accumulated clay and developed cohesive matrix strength. The now exclusively mud-rich flow resembled a viscous plug flow, which like the now deposited basal layer, thinned and then pinched out. At all times the suspension was overlain by a low-density turbidity current that formed a well-sorted, traction-structured layer made up of sediment reworked from the underlying deposit (i.e. lateral facies succession). Lastly, any clay that remained in suspension settled forming a near-bed fluid mud layer that eventually gelled depositing a mudstone cap (F4) that marks the end of a single sedimentation event.

Vertically, deposition begins with the emplacement of a coarse, graded sandstone (F1A) related to the local introduction of a single high-energy, sediment-laden vortex. This is then abruptly followed by a dramatic contraction of the jet margin and the episodic detachment of self-similar vortices that deposited a 2-7 bed-thick package made up of similar facies. Importantly, time between successive depositional events (i.e. each bed) was of sufficient duration to allow for the emplacement of the structured sandstone and overlying mudstone cap. At an even larger scale, the lateral and vertical juxtaposition of SA1 and SA2 is interpreted to reflect the abrupt lateral displacement of the axis of the main avulsion jet followed by a period of temporary stabilization. These avulsion-related strata are then abruptly overlain by a thick stack of classical turbidites (SA3), which suggests that sedimentation downflow of the avulsion node ceased, most probably due to a upflow avulsion, and as a consequence a return to more typical extrachannel deposition, specifically levee growth. Alternatively, the abrupt superposition of SA3 turbidites could reflect the depletion of a locally erodible mud-rich sea floor, quite possibly due to scour down to a sufficiently compacted subsurface layer, or simply being buried in sand.

Conclusion

At the Castle Creek study area a remarkably well-exposed section in the Isaac Formation, Windermere Supergroup was measured to document the spatial and temporal relationship between matrix-rich and matrix-poor strata. Here, a consistent lateral succession of facies, which from proximal to distal, consists of matrix-poor sandstone to clayey sandstone to bipartite bed to sandy claystone, collectively overlain by a thin-bedded turbidite and mudstone cap. These changes are interpreted to reflect particle settling in a negligibly-sheared, sand-mud suspension following detachment from the margins of an avulsion jet. Vertically, similar facies tend to preferentially stack and build up 2-7 bed-thick packages implying temporary stabilization of jet-margin dynamics. At an even larger scale facies stack to form three stratal assemblages. SA-1 consists of intercalated matrix-rich and matrix-poor strata and SA-2 of matrix-rich strata. These then alternate upward but become interrupted by several-meter-thick units consisting exclusively of classical turbidites (SA-3), and indicating a dramatic change from deposition immediately downflow of an avulsion node to more typical extrachannel levee sedimentation.

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