GeoConvention 2014 FOCUS adapt refine sustain

Depositional Continuum of Sand to Mud-Rich Basin-Floor Sandstones Associated with a Submerged Hydraulic Jump Downflow of an Avulsion Node, Upper Kaza Group, Neoproterozoic Windermere Supergroup, British Columbia, Canada

Nataša Popović[1], Robert W. Arnott[1]

1. Department of Earth Sciences, University of Ottawa, Ottawa, Ontario, Canada

Summary

Matrix-rich sandstones (25 up to >50% mud/silt) have been increasingly recognized in ancient deep-marine basin-floor strata. Beds are generally thought to be deposited from mud-rich transitional flows in a distal basin-floor setting but mechanistic details are still poorly understood, partly because details of any lateral lithological changes are poorly known. In the study area however, matrix-rich sandstones are common in proximal basin-floor strata (Upper Kaza Group) of the Neoproterozoic Windermere Supergroup (British Columbia, Canada). Here vertically-dipping, periglacial exposures provide an excellent opportunity to illustrate the stratal architecture, namely the vertical but potentially more importantly lateral lithological make-up in a unit 40 m thick and 800 m wide. From high-resolution stratigraphic and sedimentological field data as well as detailed petrographic sample analysis four major facies are recognized: matrix-rich and matrix poor sandstones, an intermediate transitional sandy-mudstone facies and thin-bedded, mostly upper division turbidites. Based on the location and frequecy of facies, the outcrop is divided into 3 major sections (S1, S2, S3) (Figure 2). S1 (~400 m wide) comprises amalgamated, structureless, matrix-poor sandstone. In S2 (~280 m wide), however, bedding is discernible and meter thick, matrix-poor Ta beds overlain sharply by one to more, up to 70 cm thick, sandy (medium sand) mudstones are common. The transition from S1 to S2 occurs over several Dm and is marked by the abrupt occurrence of abundant, large (>2 m x 1 m), irregularly shaped clasts composed of thinly-bedded turbidites or matrix-rich sandstones. The transition from S2 to S3, on other hand, is marked by a rapid (over a few Dm) and dramatic decrease in the thickness and abundance of matrix-poor beds but an increase in matrix-rich sandstones interstratified with thin-bedded turbidites, that stack to form units up to ~1 m thick. The lateral change from matrix-poor to matrix-rich sandstones is interpreted to represent a depositional continuum outboard of a submerged hydraulic jump that formed immediately downflow of an avulsion node. Sediment eroded beneath the jump rapidly charged the flow with new, mostly fine-grained sediment that dramatically and almost instantaneously changed the rheology of the flow. In addition, the flow becomes highly stratified, with coarse sand remaining in the axis, but medium and finer sand and the abundant mud being partitioned towards its margins.

Introduction

This study documents the architectural elements and stratigraphic nature of matrix-rich and genetically-related matrix-poor sandstones in the Neoproterozoic Windermere Supergroup, specifically the Upper Kaza Group. Additionally, it investigates the lateral relationship between matrix-rich and matrix-poor strata and provides important new data on the textural and mineralogical attributes of matrix-rich sandstones, matrix-poor sandstones and intermediate, transitional sandy-mudstones. Matrix-rich/mud-rich transitional flow deposits have been have been increasingly recognized in ancient deep-marine basin-floor strata and have been referred to as “linked debrites” by Haughton et al. (2003), Amy and Talling (2006), Haughton et al. (2009), “co- genetic debrite-turbidite beds” by Talling et al. (2004) and “hybrid event beds” by Hodgson (2009), Pyles and Jennette (2009). Typically these strata are reported from the distal parts and lateral parts of basin-floor turbidite systems. In this study, however, matrix rich deposits, hereafter termed “matrix-rich sandstones”, crop out in strata interpreted to have been deposited not only on the proximal part of the basin floor, but also by depositional processes that contrast significantly those proposed by earlier authors -- specifically deposition lateral to and/or outboard(?) of a submerged hydraulic jump immediately downflow of an avulsion node.

Method

Fieldwork was conducted over two six week periods from mid-July to late August 2012 and 2013 near the headwaters of Castle Creek (Caribou Mountains, B.C. Canada) (Figure1). Emphasis was placed on the careful documentation of the textural and sedimentological details of strata cropping out in 36 vertical stratigraphic sections that range from 15 to 30 m long and spaced laterally over a distance (parallel to bedding) of about 800 m in the middle part of the Upper Kaza Group at Castle Creek. Distance between logs ranges from 20 to 120 m depending on quality of exposure and rate of lateral lithological changes. In addition, stratigraphic correlations were mostly “walked-out” in the field (due to excellent outcrop exposure) and aided by the use of high-resolution aerial photographs, on which some beds could be confidently identified and traced laterally. A total of 40 petrographic samples were collected for more detailed description of grain size, grain sorting and mineralogy. Samples from matrix-rich and transitional sandy-mudstone beds were taken systematically from the bottom, middle and top of the bed to capture any upward change. Detailed point counting of 300 grains in each of 12 representative samples was done to establish a ratio of matrix:framework grains in each facies. Similarly, using an image processing program, all of the matrix-rich and intermediate samples were analyzed to further establish a matrix:framework grains ratio. This was done to clearly and quantitatively differentiate matrix-rich from matrix-poor sandstones.

Facies

Facies 1: Matrix-rich Sandstone.

These strata are easily identified in the field by several distinct lithological characteristics, namely, abrupt upward decrease in grain size and their blue-green-greyish hue. Beds are typically 10s cm thick, ranging from several cm to ~60 cm thick, and stack to form units up to a few meters thick. Beds are structureless, massive or coarse-tail graded with grain size ranging from lower medium to lower coarse sand with abundant (25% up to >50%) mud/silt matrix content and overlain abruptly by a 1-5 cm siltstone/mudstone cap (Figure 4). Petrographic examination of samples indicates that the widespread matrix is composed of chlorite, muscovite and minor silt. Bed contacts are sharp and generally planar. Dispersed bluish grey to black mudstone clasts are common and locally make up to 10-40% of the bed volume. Clasts are typically elongate and range from 3-45 cm long and 0.5-20 cm thick, but more typically are around 5-20 cm long and 0.5-2 cm thick. Clasts exhibit a well-developed fabric oriented parallel to the basal contact.

Unlike most turbidites where clay is fractionated during flow and settles from suspension during the latter stages of the flow event to create a thin mud cap (Haughton et al., 2009), matrix-rich sandstones consist of sand grains dispersed in a matrix of clay- and silt-sized particles. These conditions are interpreted to have been developed along the margins of a submerged hydraulic jump. Energetic secondary circulation within the jump deeply scoured the seabed and locally supercharged the flow with mud and silt. This fine-grained sediment along with sediment up to about medium sand and low-density (ripped-up) mudstone clasts were preferentially segregated toward and then beyond the margins of the jump. Here rapid deposition emplaced the basal matrix-rich sandstone part of each matrix-rich sandstone bed, which later became draped by mudstone deposited from suspension during the terminal, low-energy stages of the flow event (Khan and Arnott, 2010; Postma, 1986).

Facies 2: Bipartite Sandy-Mudstone with Intermediate Matrix.

Strata of Facies 2 are most common in the northwestern part of the study area and are the dominant facies in section 2 (S2) (Figure 2). Beds range from 50 to 160 cm thick and distinctively consist of a thick, basal, light coloured sandstone overlain abruptly by a thinner, darker, more mud-rich layer (Figure 5). The basal sandstone unit, which ranges from 30-120 cm thick and has a planar, flat basal contact, consists of coarse to upper medium sand grains that grades gradually upward into lower medium sand. Matrix content remains consistent throughout the bed and is of the order of 15-25% of the bed volume. Locally, irregularly shaped mudstone and sandstone clasts (3-200 cm long, 1-54 cm wide) occur in the middle part of the unit. The much finer-grained upper unit overlies a sharp, planar basal contact and ranges from 10-50 cm thick. These strata are easily identified in the field by an abrupt grain size change from lower medium sand at the top of the lower unit to fine/very-fine grained sandstone/siltstone with rare dispersed lower medium sand grains. The basal part of the fine upper unit ranges from 3-50 cm thick and consists of diffuse, discontinuously planar-laminated lower fine sandstone/very fine sandstone. This, then, is overlain by stacked light-dark coloured couplets that reflect, respectively, alternating sand-rich and mud-rich lithologies. Individual couplets are 5-12 cm thick and in their lower part composed of undulating, low-angle subtly cross-stratified lower fine sandstone/very fine sandstone capped abruptly by darker coloured silty mudstone (Figure 5).

Like strata of Facies 3, structureless sandstone at the base of each Facies 2 bed was deposited rapidly from suspension, but unlike Facies 3, immediately beyond the confines of the hydraulic jump. The abrupt upward change to the finer-grained upper unit represents initially a bypass surface that later was draped by a rhythmic alternation of low energy tractionally transported fine-grained sand followed by silty mud deposition from suspension.

Facies 3: Matrix-poor Sandstone.

Facies 3 consists of massive, structureless, lower coarse sandstone with dispersed upper very coarse sand grains and rare granules that grades gradually upward to lower medium sandstone with uncommon dispersed coarse grains. Matrix is generally of the order of 15% or less of total volume (Figure 4). Bed thickness varies widely and ranges from 10 cm to ~2 m thick. Where visible, basal contacts are typically planar and sharp, although scours 15 cm deep and 1-4 m long are observed locally. In the southeast part of the study area (S1) sandstone beds of Facies 3 are amalgamated and form units more than a few meters thick. In contrast, matrix-poor sandstones in the northwest section (S3) range from 10-60 cm thick and are commonly separated by a 2-10 cm thick layer of silty mudstone or strata of Facies 1 or 4.

Massive, structureless, coarse-grained sandstones of Facies 3 are interpreted to be equivalent to the Ta division in a Bouma turbidite or the S3 division in a Lowe sequence, and represent suspension deposition from high-density turbidity current (e.g. Sylvester and Lowe 2004). The massive, structureless nature of the strata implies that rates of suspension fallout were sufficiently high that bed form development was suppressed or visible evidence of their presence muted (Arnott and Hand, 1989; Lowe, 1982). Forming a depositional continuum with Facies 1 and 2, sandstones of Facies 3 are interpreted to represent the residuum of sand that was unable to escape the confines of the hydraulic jump and accumulated in its axial part.

Facies 4: Thin-bedded Turbidites.

In the study area strata of Facies 4 consist of upper-division turbidites (Tcde), although a basal planar laminated unit (Tb) is common. Beds grade from upper/lower fine sandstone in the Tb/Tc layers to very fine sandstone overlain by siltstone then mudstone in the Td and Te layers (Figure 5). Grain size never exceeds lower fine sandstone. Thin-bedded turbidites often stack to form units ranging from 10 cm to ~1.5 m thick. Strata of Facies 4 occur throughout the study area but are most common in the northwestern part of the study area (S2 and S3) where they form interbeds in strata of Facies 1 and 2.

Facies 4 is interpreted to be deposited by dilute, low density turbidity currents. Where it is interbedded with strata of Facies 1 or 2 indicates low-energy sedimentation events interspersed with energetic hydraulic jump related sedimentation events.

Conclusions

The lateral change from matrix-poor to matrix-rich sandstones is interpreted to represent a depositional continuum within and outboard of a submerged hydraulic jump that formed immediately downflow of an avulsion node. Fine sediment eroded in the jump abruptly changed the rheology of the flow, which became manifest not only in the abrupt lateral decrease in grain size, but more profoundly the occurrence of matrix-poor transitioning rapidly into matrix-rich rich sandstones along its periphery. This study, therefore, provides an alternative explanation for the origin and depositional significance of matrix-rich sandstones observed in deep-marine turbidite systems.

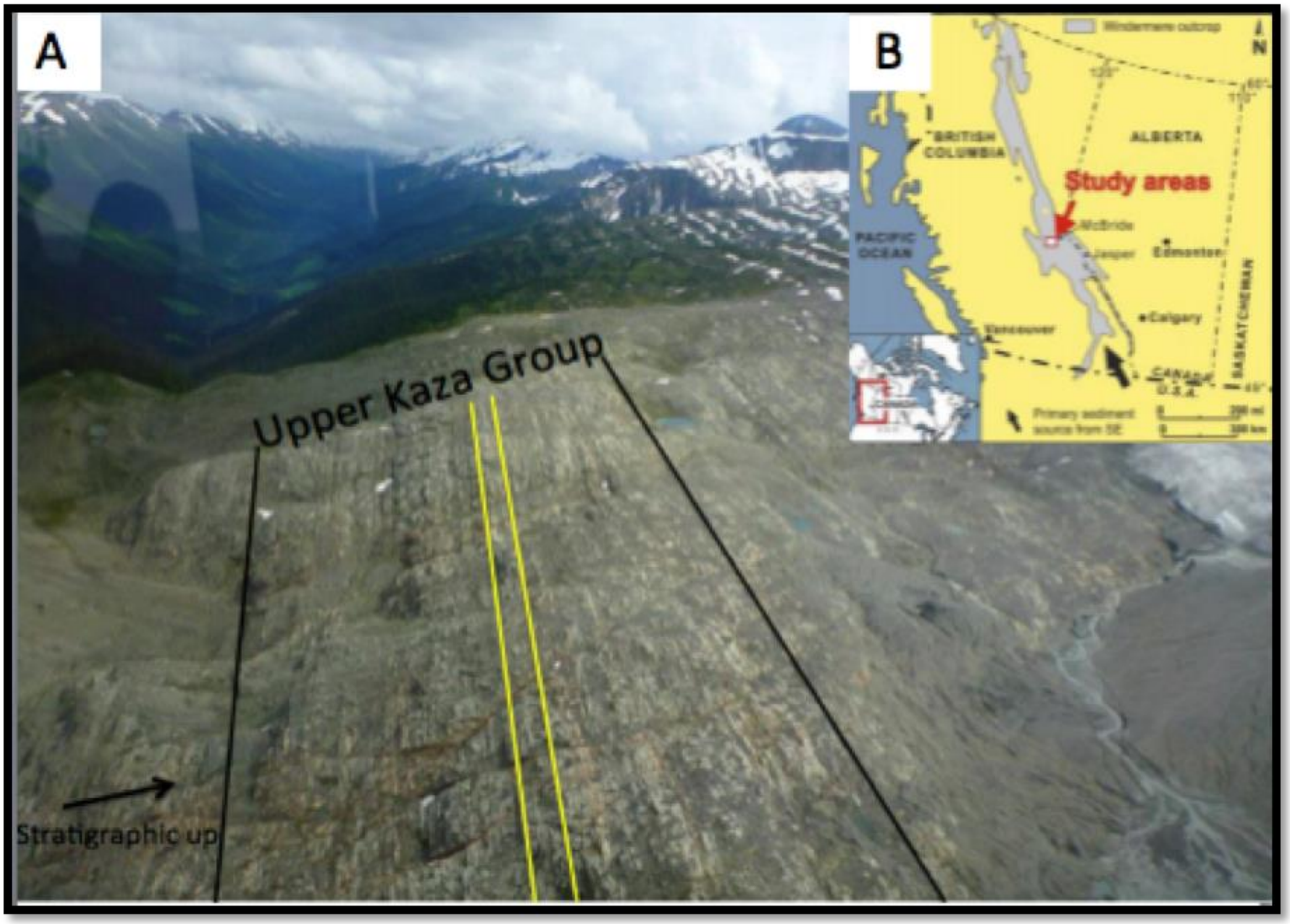
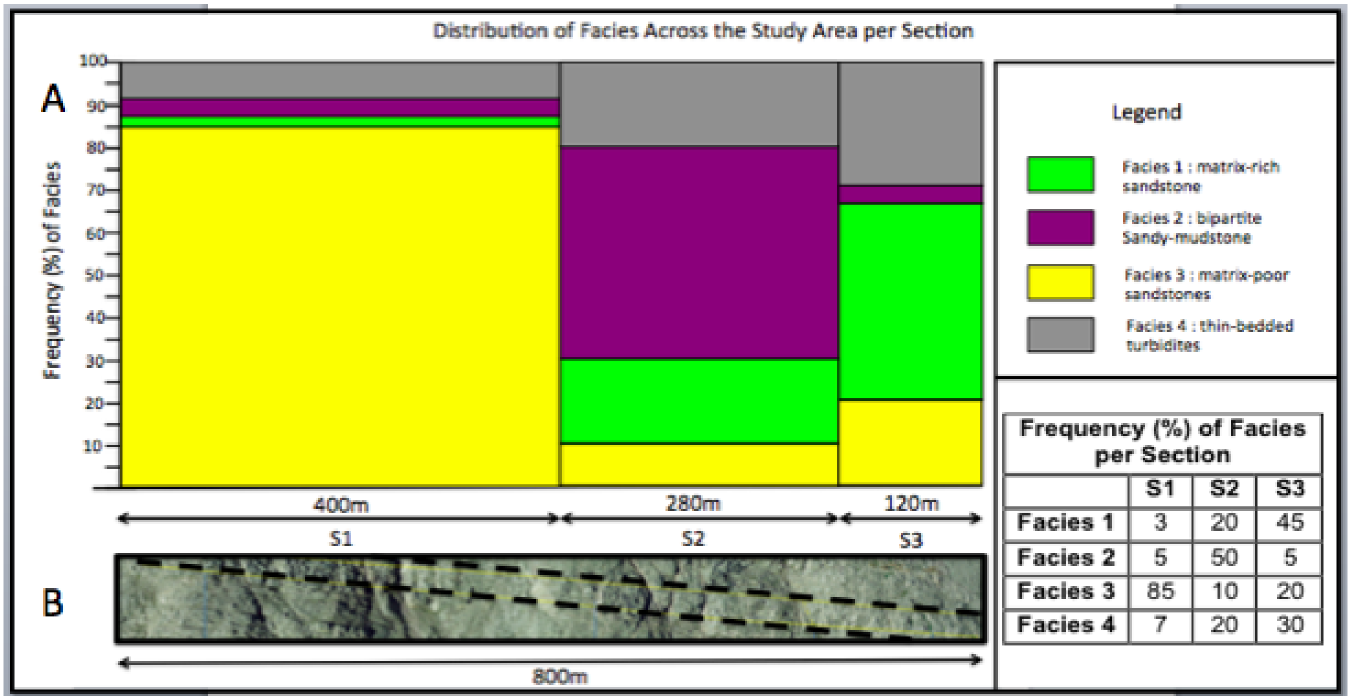


Figure 1: A) Aerial view of the Upper Kaza Group at the Castle Creek outcrop. The study area of this research is focused in the area between the two yellow lines. B) Location of the Castle Creek study area, Caribou Mountains, east-central B.C., Canada. Windermere strata distribution from Ross (1991).



Frequency (%) of Facies per Section

	S1	S2	S3
Facies 1	3	20	45
Facies 2	5	50	5
Facies 3	85	10	20
Facies 4	7	20	30

Figure 2: Based on the location and distribution of facies, the study are has been separated into 3 sections. A) Graphical representation of the percentage of each facies within each section. B) Aerial photograph of the entire 800m wide study area.

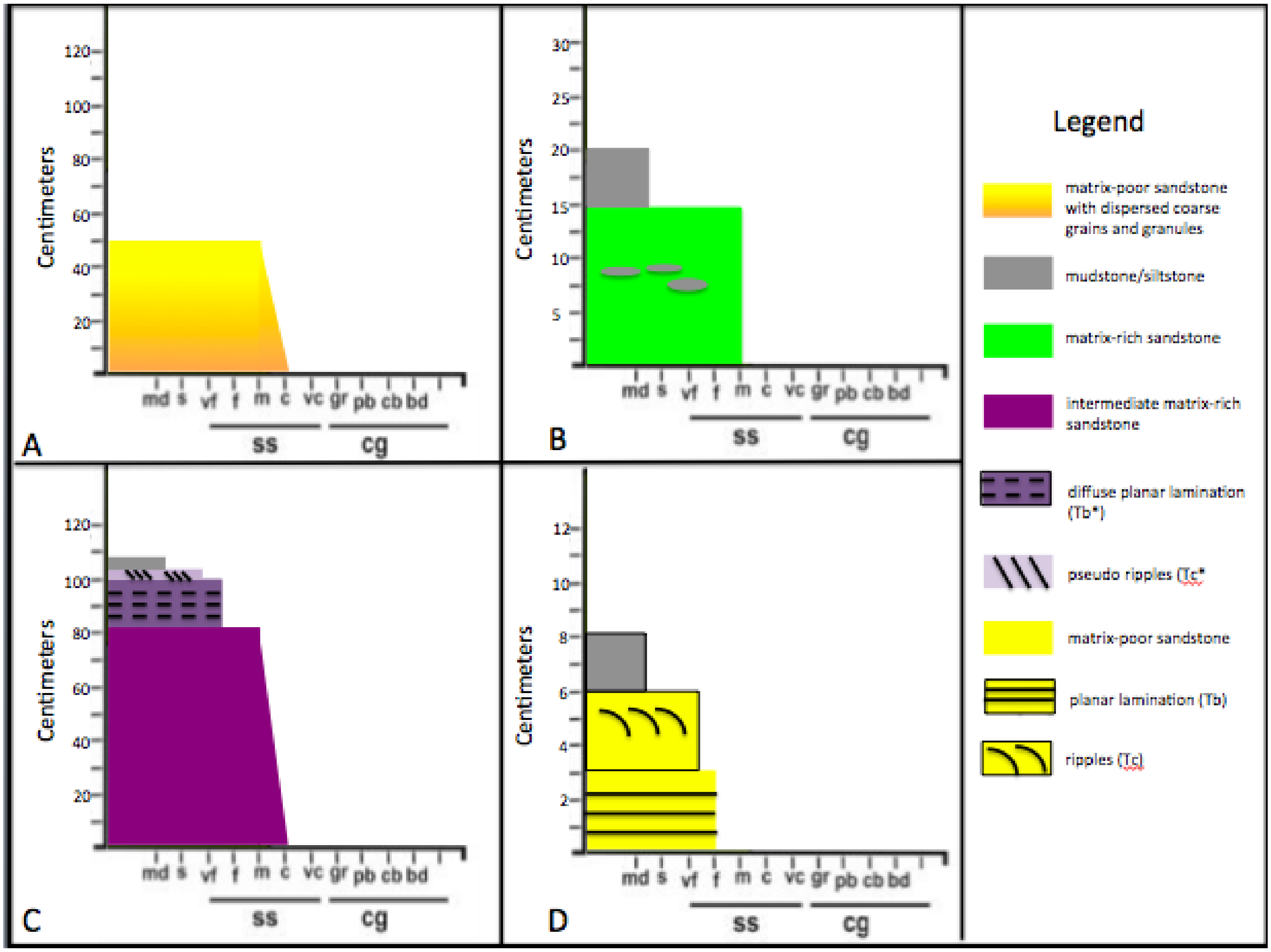


Figure 3: Idealized logs of each facies. A) Matrix-poor sandstone with dispersed coarse grains and granules (Facies 3). B) Matrix-rich sandstone with dispersed mudclasts and silt/mud cap (Facies 1). C) Bipartite sandy-mudstone consisting of a basal Ta-like unit with an intermediate amount of matrix and an upper unit comprised of diffuse planar lamination, capped by silt/mud (Facies 2). D) Tbcde turbidite.

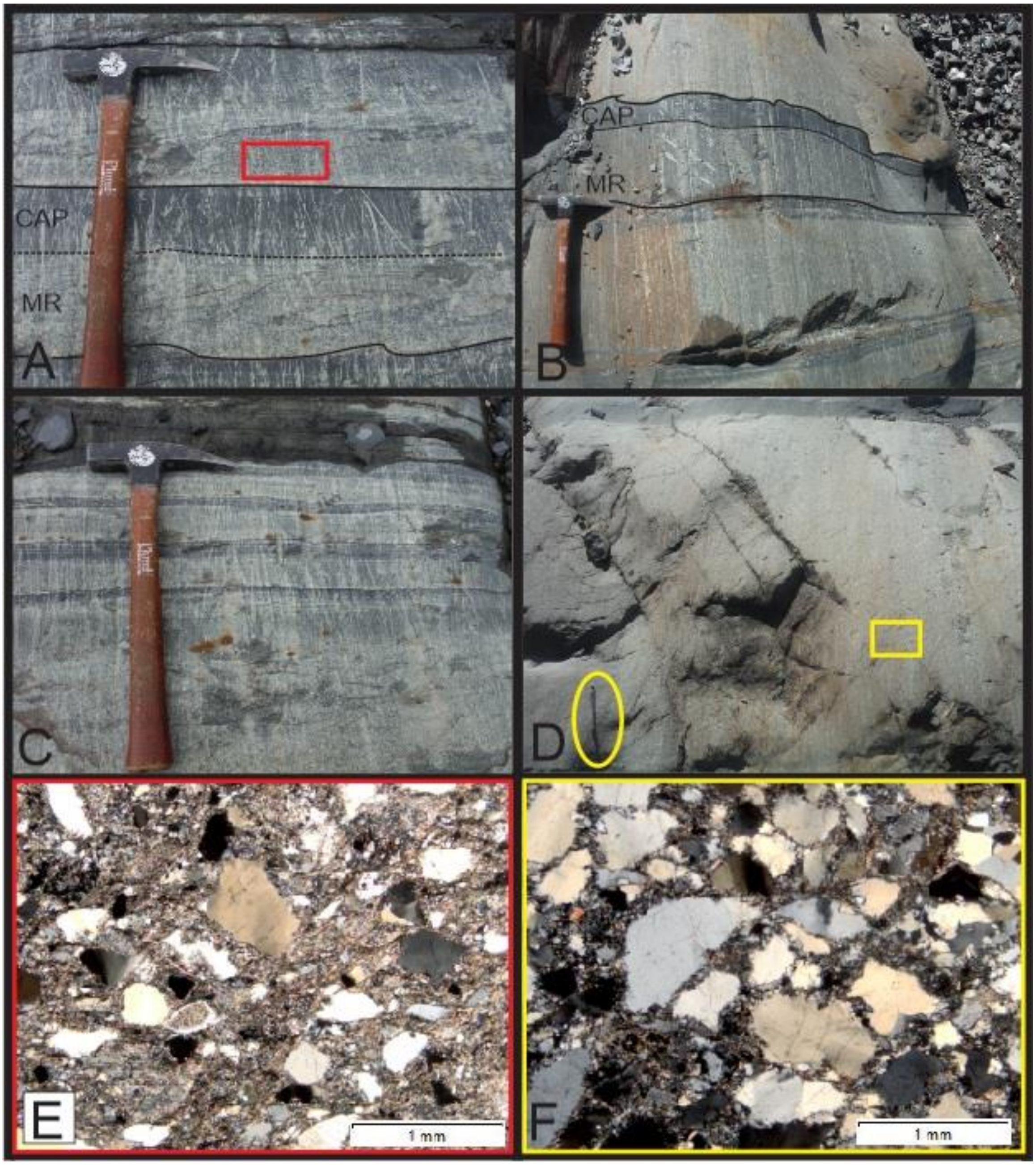


Figure 4) Representative photographs of facies. A) Two matrix-rich sandstones stacked on top of one another. Note the mudclast stringers through the middle of the upper bed. B) showcases a matrix-rich beds of a larger scale. C) A stack of small-scale matri-rich beds. D) Representative photograph of a matrix-poor sandstone, elipse is a mechanical penciel for scale. E) Cross-polarized photomicrograph of the matrix-rich bed showcased in A. Red box in A represents where the sample was taken from. F) Cross-polarized photomicrograph of the matrix-poor bed showcased in D. Yellow box in D represents the location of the sample. Note the difference in matrix content between E and F.

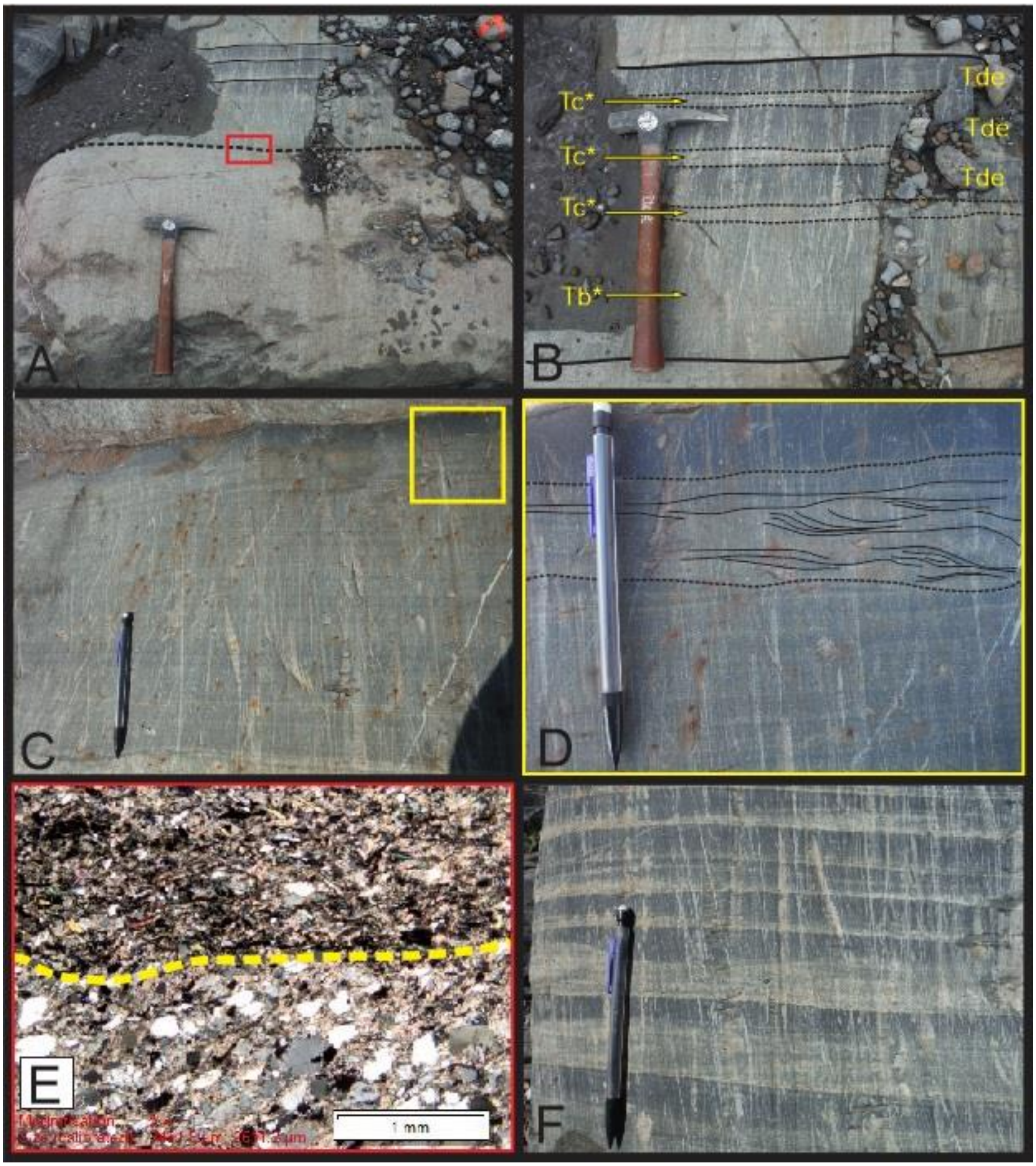


Figure 5: Representative field photographs of facies. A) A complete bipartite sandy-mudstone. The dash line represents the abrupt change from the basal Ta-like unit into the more fine-grained diffusely laminated unit. B) Up-close look at the upper unit pictured in A. C) A second example of the upper unit common in the bipartite facies. D) Up-close view of the ripple-like layer (Tc*). The yellow box in C represents the area shown in D. E) Cross-polarized photomicrograph of the abrupt boundary between the basal and upper unit of the bipartitebed shown in A (represented by the red box). F) Representative photograph of Tbcde thin-bedded turbidites.

Acknowledgments

Special Thanks to Dr. Bill Arnott and the whole Windermere Consortium.

References

Arnott, R.W.C., 2007, Stratigraphic architecture and depositional processes of a proximal crevasse splay and genetically related, sinuous channel fill, Isaac Formation, British Columbia, Canada: in T. H. Nilsen, R. D. Shew, G. S. Steffens, and J. R. J. Studlick, eds., Atlas of deep-water outcrops: AAPG Studies in Geology 56.

Arnott, R.W.C., 2012 ,Deep-marine sediments and sedimentary systems. Facies Models

Arnott, R.W.C., and Hand, B.M., 1989, Bedforms, primary structures and grain fabric in the presence of suspended sediment rain: Journal of Sedimentary Petrology, v. 59, no. 6, p. 1062-1069.

Baas, J.H. (2004). Conditions for formation of massive turbiditic sandstones by primary depositional processes. Sedimentary Geology, v. 166, pp. 293 - 310.

Baas, J.H., Best, J.L., and Peakall, J., 2011, Depositional processes, bedform development and hybrid bed formation in rapidly decelerated cohesive (mud–sand) sediment flows: Sedimentology, v. 58, p. 1953–1987.

Haughton, P.D.W., Barker, S.P., and McCaffrey, W.D., 2003, 'Linked' debrites in sand-rich turbidite systems—Origin and significance: Sedimentology,v. 50, p. 459–482.

Haughton, P., Davis, C., McCaffrey, W., and Barker,S., 2009, Hybrid sediment gravity flow deposits— Classification, origin and significance: Marine and Petroleum Geology, v. 26, p. 1900–1918

Khan, Z.A. and Arnott, R.W.C. (2010). Stratal attributes and evolution of asymmetric inner- and outer-bend levee deposits associated with an ancient deep-water channel-levee complex within the Isaac Formation, southern Canada. Marine and Petroleum Geology, pp. 1 - 19.

Lowe, D.R., 1982, Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents: Journal of Sedimentary Petrology, v. 52, p. 279-297.

Lowe, D.R. and Guy, M. (2000) Slurry-flow deposits in the Britannia Formation (Lower Cretaceous), North Sea; a new perspective on the turbidity current and debris flow problem.
Sedimentology, 47, 31–70.

Lowe, D.R., Guy, M. and Palfrey, A. (2003) Facies of slurry flow deposits, Britannia Formation (Lower Cretaceous), North Sea: implications for flow evolution and deposit geometry. Sedimentology, 50, 45–80.

Pyles, D.R., and Jennette, D.C., 2009, Geometry and architectural associations of co-genetic debrite-turbidite beds in basin-margin strata, Carboniferous Ross Sandstone (Ireland): Applications to reservoirs located on the margins of structurally confined submarine fans. Marine and Petroleum Geology.v. 26, p. 1974-199

Ross, G.M., 1991, Tectonic setting of the Windermere Supergroup revisited: Geology, v. 19, p. 1125-1128.

Ross, G.M., Bloch, J.D., and Krouse, H.R., 1995, Neoproterozoic strata of the southern Canadian Cordillera and the isotopic evolution of seawater sulfate: Precambrian Research, v. 73, p. 71-99.

Ross, G.M., and Arnott, R.W.C., 2007, Regional Geology of the Windermere Supergroup, Southern Canadian Cordillera and Stratigraphic Setting of the Castle Creek Study Area, in T. H. Nilsen, R. D. Shew, G. S. Steffens, and J. R. J. Studlick, eds., Atlas of Deep-Water Outcrops: AAPG Studies in Geology 56.

Schwarz, E., and Arnott, R.W.C., 2007, Anatomy and evolution of a slope channelcomplex set (Neoproterozoic Isaac Formation, Windermere Supergroup, southern Canadian Cordillera): implications for reservoir characterization: Journal of Sedimentary Research, v. 77, p. 89–109.

Smith, M.D., 2009, Stratigraphic and geochemical evolution of the Old Fort Point Fm., southern Canadian Cordillera: the deep-marine perspective of Ediacaran post-glacial environmental change. Ph. D. Thesis, University of Ottawa.

Smith, M.D., Arnott, R.W.C., and Ross, G.M. (2009). The Neoproterozoic Old Fort Point Formation, Southern Canadian Cordillera. Canadian Society of Petroleum Geologists, Reservoir, v. 35.

Southard, J.B., Boguchwal, L.A. (1990). Bed configuration in steady unidirectional water flows. Part 2. Synthesis of flume data. Journal of Sedimentary Petrology, v. 60, pp. 658 - 679.

Stow, D.A.V. and Bowen, A.J. (1980) . A physcial model for the transport and sorting of fine-grained sediments by turbidity currents. Sedimentology, v. 27, 31 - 46.

Stow, D.A.V., and Johansson, M., 2000, Deep-water massive sands: nature, origin and hydrocarbon implications: Marine and Petroleum Geology, v. 17, p. 145-174.

Sylvester, Z., and Lowe, D.R., 2004, Textural trends in turbidites and slurry beds from Oligocene flysch of the East Carpathians, Romania. Sedimentology, v. 51, p.944-972.

Talling, P.J., Amy, L.A., Wynn, R.B., Peakall, J., and Robinson, M., 2004, Beds comprising debrite sandwiched within cogenetic turbidite: origin and widespread occurrence in distal depositional environments, Sedimentology, v. 51, p163-194.