Sedimentologic and Petrographic Evidence of Flow Confinement in a Passive Continental Margin Slope Channel Complex, Isaac Formation, Windermere Supergroup, British Columbia, Canada

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Summary

Along the base of passive continental margins, like the Canadian east coast, extensive deep-water clastic turbidite systems are present. Through the 21st century these systems have been increasingly recognized as prolific petroleum reservoirs and currently represent about 20-30% of global production (U.S. Energy Information Administration, 2016). In spite of their excellent resource potential, deep-marine turbidite systems also come with many uncertainties and substantial drilling costs. In order to reduce economic risk and improve exploration success, petroleum geologists have turned to the ancient deep-marine sedimentary record to find meaningful analogues to describe passive margin deep-water turbidite systems. These deposits are often classified using the Bouma (1962) turbidite model; a generally upward-fining succession composed of five sharply bounded layers, each exhibiting a unique assemblage of predictable sedimentary structures and textures. In the Windermere Supergroup, however, in addition to classical turbidites, another type of strata, which superficially resemble turbidites, are observed. Where fully developed these strata consist of a basal structured or massive sandstone (F1) overlain gradationally by rhythmically interstratified sandstone and mudstone (F2). This layer is then overlain gradationally by distinctively interstratified, fine-grained sandstone grading to massive silty mudstone (F3). These very different and distinctive characteristics are interpreted to be the result flow confinement in a slope channel complex.

Introduction

The Neoproterozoic (740-569 Ma) Windermere Supergroup in the Cariboo Mountains, British Columbia is one of the best developed and best exposed examples of an ancient passive margin turbidite system in the world. At the Castle Creek study area recently deglaciated, vertically dipping strata crop out for 8 km parallel to bedding and 2.5 km perpendicular to bedding and provide an unparalleled opportunity to study the deep-marine sedimentary record on scales that range from millimetres (sub-seismic-scale) to kilometres (seismic-scale).

Strata have been tectonically deformed and subjected to low-grade (sub greenschist to greenschist facies) regional metamorphism (Murphy, 1987). Nevertheless, primary sedimentary structures, even down to millimetre-scale laminae, are well preserved, in spite of the fact that primary textural characteristics have in some cases been completely modified by recrystallization.

In the deep-marine the primary sediment-transporting agent is a turbulent sediment-laden suspension termed a turbidity current, and whose depositional product is a classical (Bouma) turbidite. Where fully developed these deposits comprise five sharply bounded layers, or divisions: the basal layer consists of massive or normally graded sandstone (T_a) overlain successively by planar-laminated sandstone (T_b), high-angle, ripple cross-stratified sandstone (T_c), subtly parallel-laminated siltstone (T_d), and finally massive mudstone (T_e). This, however, contrasts strata observed in the study area that consist of three, gradationally bounded layers and whose sedimentological structures and textures differ from those in classical turbidites. The objective of this study, therefore, is to describe in detail these distinctive strata and to explain their physical origin and how it differs to that for classical turbidites.

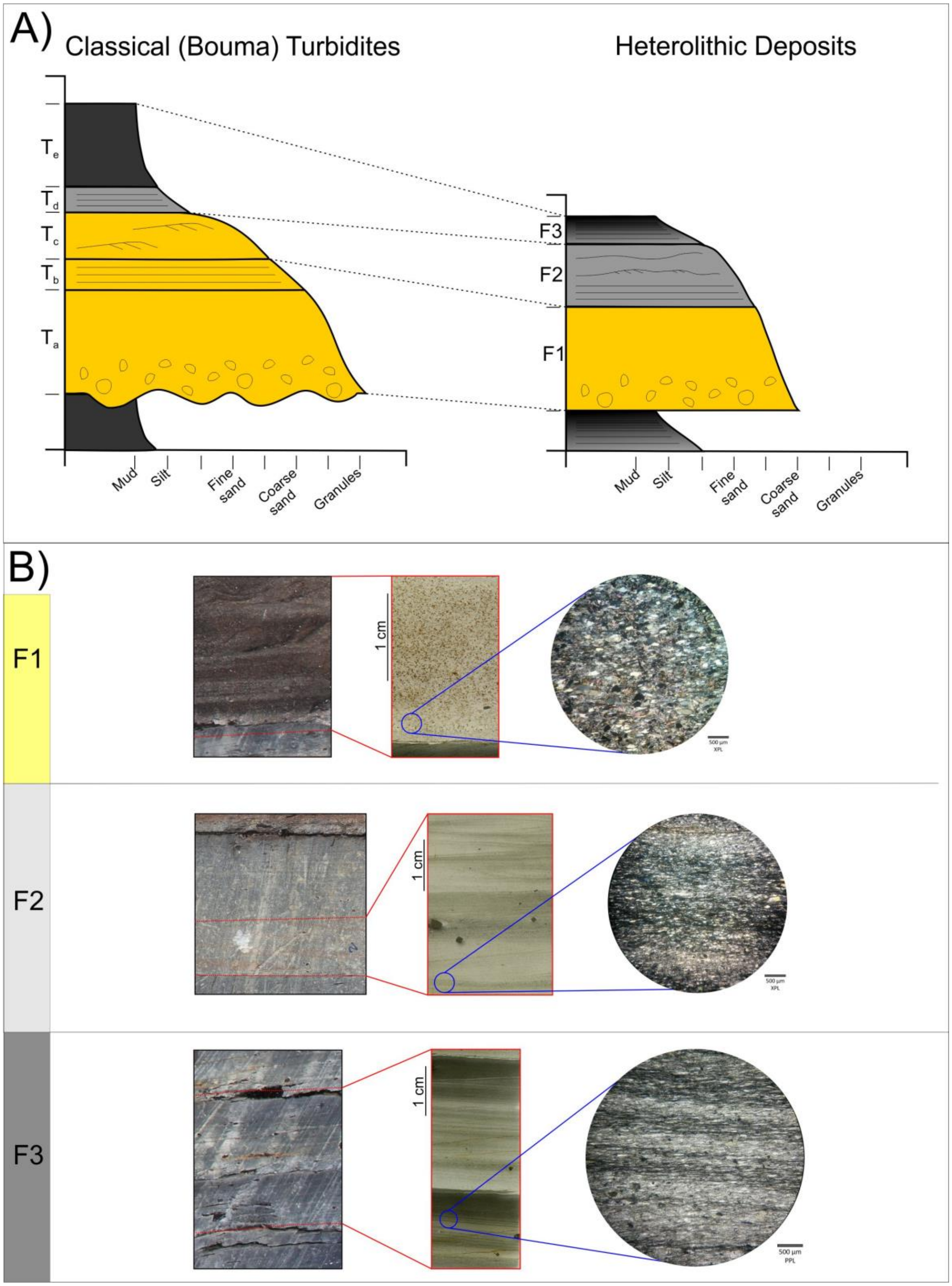

Figure 1: A) Schematic and proposed correlation of the divisions in an idealized classical (Bouma) turbidite and the heterolithic strata described in this study. B) Outcrop photo, thin section image, and photomicrograph of each of the stratal components in a heterolithic deposit.

Theory and/or Methods

Field-based bed-by-bed measurement and detailed description of strata was then followed by mapping using high-resolution aerial photos and drone footage to delineate vertical and lateral trends in stratigraphy. Also, samples for petrographic analysis were collected and later studied to determine microscopic fabric and textural characteristics, including grain size, grain sorting, mineralogical composition, and lamina-scale physical sedimentary structures. These macroscopic and microscopic features were then used to identify any vertical and lateral trends in matrix content, sedimentary structures, and lithology.

Examples

The study area crops out for over 450 metres laterally and can be subdivided into two parts. The first part consists of a basal amalgamated unit overlain by a heterolithic unit capped sharply by a thick succession of fine-grained, thin-bedded classical turbidites (*Fig. 2*). The basal amalgamated unit is 15 metres thick, composed of amalgamated coarse-grained sandstone to pebble conglomerate, and interpreted to be a channel complex (informally termed IC0 by Navarro, 2016). The second part occurs at the same stratigraphic level, but 250 metres to the northwest. Here strata consist of a thick succession of rhythmically interlaminated, well-sorted, very fine-grained sandstone overlain sharply by mudstone that distinctively lack traction transport structures. Although the contact between the two parts is covered, such a dramatic lithological change over only a few hundred metres suggests that IC0 scoured these fine-grained strata and then became partly filled with the amalgamated unit. These strata grade upward over about one metre into the heterolithic unit.

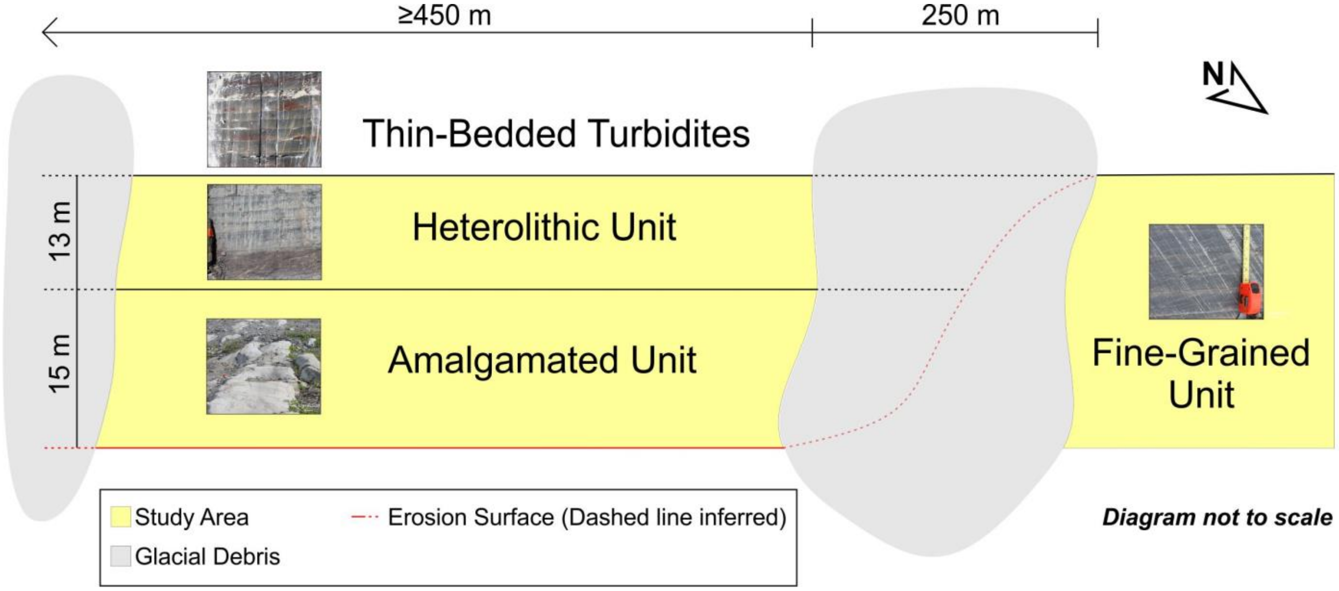

Figure 2: Schematic cross-section of the study area denoting the two general parts of the outcrop. Note that the subvertical white lines in the photos are glacial striations.

Stratigraphically upward, the heterolithic unit forms a 13 metre-thick succession that comprises 2-5 metre-thick bedsets in which the basal F1 layer fines and thins, the medial F2 portion thins, and the upper F3 part thickens. Strata in this unit exhibit some of the characteristics of classical Bouma turbidites, but also a number of unique features. The basal layer (F1) is typically massive or planar/wavy-stratified, upper very coarse- to lower very fine-grained sandstone. It ranges from 1-112 cm (average 15 cm) thick and has low matrix content (silt and clay <10%), and is potentially correlative with the A- and B-divisions of classical turbidites (*Fig. 1A*) (Bouma, 1962). It then is overlain gradationally by wavy/cross- or planar-stratified, upper medium- to lower very fine-grained, matrix-rich (30-40%) sandstone rhythmically interstratified with sandy mudstone (F2). This stratal layer, which ranges from 0.5-34.5 cm (average 6 cm) thick, superficially appears similar to the C-division of classical turbidites (*Fig. 1A*), however it lacks the characteristic high-angle cross-stratification and instead is low-angle or wavy. This, then, is capped by a 0.5-15 cm (average 3.4 cm) thick layer (F3) typically composed of three gradationally-bounded parts: matrix-rich (60-70%), subtly planar stratified, fine- to very fine-grained sandstone, overlain by planar pinstripe laminated sandy to silty mudstone, overlain by massive silty mudstone. F3 commonly stacks to form packages up to 16 layers thick. Strata in the F3 layers are ubiquitously planar stratified with well defined (*Fig. 1B*) and laterally continuous (>100 m) bands of sand, silt, and mud that contrast the typically laterally discontinuous and finer-grained nature of laminae that make up the D-division in classical turbidites (Stow and Bowen, 1978). The gradational transition from planar-stratified sandy mudstone to massive mudstone contrasts the sharply bounded contact between the D- and E-divisions in a classical turbidite (*Fig. 1A*) (Bouma, 1962).

Collectively, the lithological difference between strata in the heterolithic unit and classical turbidites is interpreted to be a consequence of flow confinement. Here two-way confinement was provided by the escarpment that had been sculpted by IC0 in the fine-grained unit to the northwest, and growth of a levee associated with a younger, but out of the plane of the outcrop channel located to the southeast. Flows that overspilled the new channel and then over the developing levee eventually encountered the flow reflected off the escarpment. The interaction of the incident (from the channel) and reflected flow (from the escarpment) created a local area of complex flow and depositional conditions, which here is manifested as the heterolithic unit. With continued deposition the relief of the escarpment became reduced and as a consequence the reflected flow diminished. Later the development of an even younger channel further to the southeast, and the flattening of the local sea floor, allowed overspill flows to move unobstructed and unconfined and deposit the thin-bedded turbidites that cap the study area.

Conclusions

This study investigates a submarine channel fill in an ancient deep-marine turbidite system and how its many macroscopic and microscopic features differ from those exhibited by classical Bouma turbidites. Presently, these strata remain poorly understood, in part because of a paucity of well exposed, areally extensive (vertically and laterally) outcrop examples around the world. Here these strata are interpreted to be a consequence of flow confinement, and more specifically, the depositional product of the interaction of incident overspill flows from an adjacent channel and those same flows but reflected off local seafloor topography. The ability to recognize the distinctive lithological characteristics of these heterolithic strata, but equally, appreciate and understand their interpretive significance, will aid in modelling these sub-seismic features, which also may be important in predicting reservoir compartmentalization and fluid flow pathways in hydrocarbon reservoirs hosted in submarine channel complexes.

Acknowledgements

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References

Bouma, A. H. (1962). Sedimentology of Some Flysch Deposits. Amsterdam, Elsevier.

Murphy, D. C. (1987). Suprastructure/infrastructure transition, east-central Cariboo Mountains, British Columbia: geometry, kinematics and tectonic implications. *Journal of Structural Geology, 9*(1), 13-29.

Navarro, L. (2016). *Stratigraphic architecture, depositional processes and reservoir implications of the basin floor to slope transition, Neoproterozoic Windermere turbidite system, Canada* (Unpublished doctoral dissertation). University of Ottawa, Ottawa, Ontario.

Stow, D. A., and Bowen, A. J. (1978). Origin of lamination in deep sea, fine-grained sediments. *Nature, 274*(5669), 324.

U.S. Energy Information Administration. (2016). Offshore oil production in deepwater and ultra-deepwater is increasing. Retrieved from http://www.eia.gov/todayinenergy/detail.php?id=28552