

Organic Carbon Sequestration in Deep Marine Levees and Implications for Hydrocarbon Source and Reservoir Potential

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Summary

In levee deposits of the Neoproterozoic Windermere Supergroup in B.C., Canada, total organic carbon content is highly variable and ranges from <0.1% to 1.7% (uncorrected for effects of greenschist metamorphism). Analysis of these strata using SEM imaging shows that carbon occurs primarily as nano-scale carbon coatings on clay grains. Because mud is the dominant grain size in virtually all deep-marine turbidite systems, and clay minerals have exceptionally high surface area-to-volume ratio, the amount of organic carbon sequestered by adsorption onto clay mineral surfaces may be significant. During periods of passive margin development, such as the breakup of Rodinia during the Neoproterozoic, the formation of extensive continental margin shelves and downslope turbidite systems would result in the development of expansive source and sinks for fine-grained sediment and organic carbon, and in turn potential hydrocarbon source rocks. This work integrates field-based observations with geochemical analyses and links primary organic productivity in marine shelf environments with deep marine transportation and depositional processes to better understand the distribution and accumulation of organic carbon in deep marine depositional systems.

Theory and Methods

Modern deep-marine levees have been shown to contain a large proportion of the world's total buried organic carbon - for example, 20% is sequestered annually in deep marine levee deposits of the modern Bengal fan alone (Galy et al., 2007; Baudin et al., 2017). However, few studies have attempted to assess this in ancient deep-marine sedimentary rocks, or to appraise their potential as hydrocarbon source rocks. Deep-marine levees are areally extensive features that commonly extend up to a few tens of kilometres beyond the margins of the coeval channel and experience exceptionally high rates of sedimentation, making them ideal sites for significant carbon burial. However, levees have received little research attention compared to the adjacent channels – an artefact of generally poor exposure in the ancient rock record and widely-spaced control points in the modern. Because of this bias many important features of levees remain poorly documented.

At the Castle Creek study area in B.C., Canada, levee deposits of the Neoproterozoic Windermere Supergroup are vertically dipping and exceptionally well exposed due to glacial polishing, allowing for detailed observations to be made at scales ranging from millimeters to hundreds of meters vertically and along strike. This makes comprehensive examination and description of lateral and vertical lithological variation and stratal geometries possible, which is critical to understanding and modelling depositional processes and reservoir geometry and continuity. In addition, mudstone samples can be used for various geochemical analyses, including total organic carbon (TOC), elemental geochemistry, and stable isotope analysis.

Results and Observations

TOC ranges from 0.04 – 1.7% in levee deposits at Castle Creek. These values are uncorrected for the effects of greenschist metamorphism, which is estimated to have resulted in the loss of 50 – 75% of the original organic material (Smith, 2009; Hayes et al., 1983), indicating that depositional values may initially have been as high as almost 7%. High TOC was recorded in both mud-rich and sand-rich facies (Figure 1) but is less common in sand-rich strata. Sand beds with elevated TOC are usually carbonate-cemented Tbcde turbidites with distinctive black interlaminae. Analysis of these strata using a scanning electron microscope (SEM) shows that carbon occurs in three main forms: (i) discrete sand-sized amorphous particles; (ii) sand-sized organomineralic aggregates; and (iii) nano-scale carbon coatings on clay grains. The amorphous carbon particles and organomineralic aggregates are interpreted to be detrital grains sourced from disaggregated bacterial mats that grew on the continental shelf before being remobilized downslope by turbidity currents. However, carbon in these coarser-grained forms is relatively uncommon; they are absent in mudstones and only occur as very dispersed particles in sand-rich strata. Additionally, the black interlaminae, where organic matter is intuitively assumed to be concentrated, are instead composed principally of clay minerals with abundant dispersed silt and sand-sized quartz grains. Many of the clay minerals in these bands, in addition to those that comprise other organic-rich levee mudstones in the study area, are surrounded by nanometer-scale black rims related to adsorbed carbon-rich films on clay mineral surfaces, and therein the primary occurrence of organic carbon in these rocks (Figure 2). This organic material is interpreted to have originated as freely suspended micro- and nano-scale organic compounds and extracellular polymeric substances (EPS) that made up part of the dissolved organic carbon pool in the upper water column over the continental shelf and further offshore. These particles then became physically adhered and/or chemically adsorbed onto the surface of clay minerals and subsequently were resedimented by suspension settling and active transport into the deep sea. Accumulation by suspension settling would have been slow and also more or less uniform across the seafloor. However in the case of active transport, due to their low density, organic material and fine-grained clay minerals would be preferentially transported in the upper portion of turbidity currents, and hence be more likely to overspill the channel margin and become concentrated in the levees, where because of high sedimentation

rates become rapidly buried and therefore protected from extensive oxidative and microbial degradation (Figure 3).

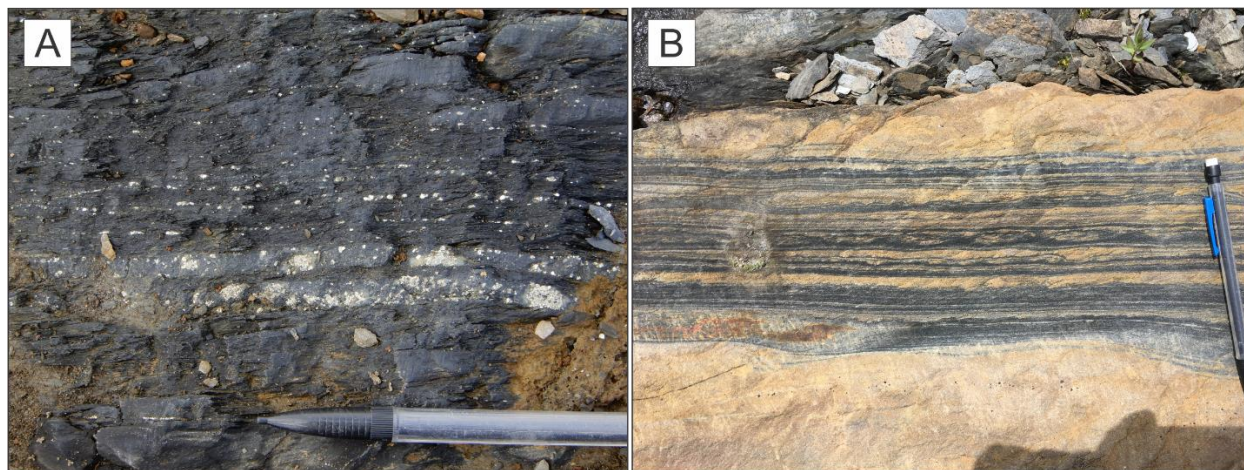


Figure 1. A) Outcrop photo of an organic-rich levee mudstone with abundant framboidal pyrite. B) Outcrop photo of an organic-rich sandstone – organic carbon is concentrated within the black laminae and is closely associated with clay minerals.

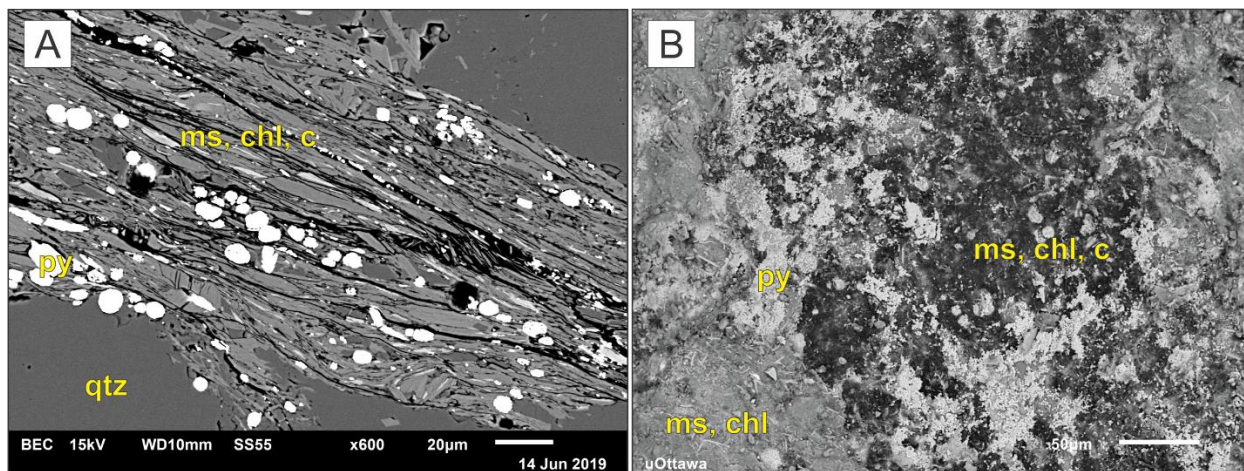


Figure 2. A) Backscattered electron micrograph of an organic-rich sandy claystone (perpendicular to bedding). Nano-scale rims of carbon (black) surround most of the clay particles (muscovite, chlorite). B) Backscattered electron micrograph of an organic-rich mudstone (parallel to bedding). Clay particles (dark grey, cloudy to needle-like in appearance) and framboidal pyrite (light grey) surrounded by organic carbon (black).

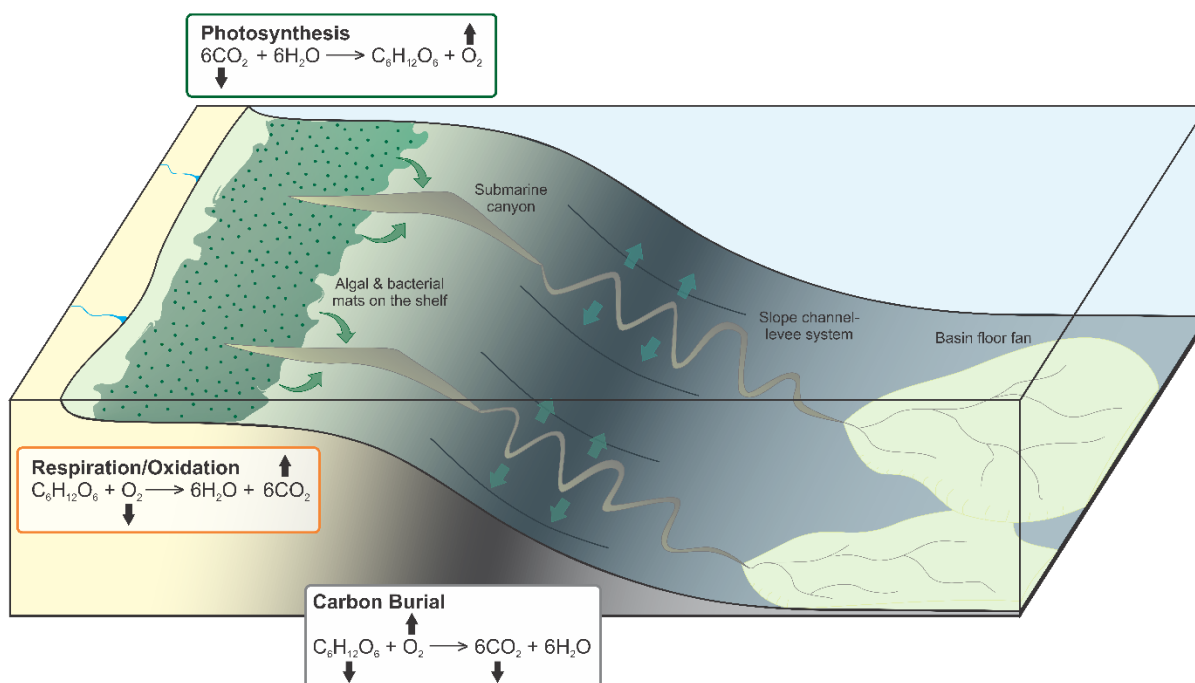


Figure 3. Depositional model showing the origin, transport, and deposition of organic material from the shelf to deep-marine leveed slope channels, and the relative impact of this process on the carbon budget (arrows indicate which products are consumed or released in each process).

Conclusions

Levees are major depocenters of organic material, which is sequestered in both mudstones and sandstones in a variety of forms, but which predominantly occurs as nano-scale carbon films adsorbed onto clay mineral surfaces. Depositional TOC values high enough to be of potential economic value have been measured throughout levee strata at Castle Creek, which, combined with the expansive area covered by levee deposits, represents a significant reservoir for organic carbon and potential hydrocarbon source rocks. The combination of high-quality outcrop data and advanced geochemical analyses will improve our understanding of carbon sequestration and cycling within these complex deep marine slope systems, and therein have important implications for assessing and quantifying hydrocarbon source rock potential.

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References

- Baudin, F., Stetten, E., Schnyder, J., Charlier, K., Martinez, P., Dennielou, B., and Droz, L., 2017. Origin and distribution of the organic matter in the distal lobe of the Congo deep-sea fan—A Rock-Eval survey. *Deep Sea Research Part II: Topical Studies in Oceanography*, v. 142, p. 75-90
- Galy, V., France-Lanord, C., Beyssac, O., Faure, P., Kudrass, H., and Palhol, F., 2007. Efficient organic carbon burial in the Bengal fan sustained by the Himalayan erosional system. *Nature*, v. 450, p. 407–410.
- Hayes, J.M., Kaplan, I.R., and Wedeking, K.W., 1983. Precambrian organic geochemistry; preservation of the record, *in* J.W. Schopf, ed.: Princeton, Princeton Univ. Press.
- Smith, M.D., 2009. Stratigraphic and geochemical evolution of the Old Fort Point Formation, southern Canadian Cordillera: The deep-marine perspective of Ediacaran post-glacial environmental change: Ph.D. thesis, University of Ottawa, 430 p.