Occurrence and Diagenesis of Organic-rich Strata in Deep Marine Levees

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Summary

In east-central British Columbia levee deposits of the Neoproterozoic Windermere Supergroup contain reconstructed depositional TOC values high enough to be potential petroleum source rocks. Although levee deposits are dominated by thin-bedded turbidites, organic material is sequestered in both mudstones and clay-rich laminae in sandstone interbeds. Burial compaction would significantly reduce the porosity of the organic-rich mudstones but have a lesser impact on interbedded sandstone. However, despite having high porosity and permeability at the time of deposition, early diagenetic cementation related to organic matter decomposition within these sandstones significantly reduced porosity and permeability prior to hydrocarbon generation, therefore reducing reservoir quality. This work seeks to better understand diagenetic processes in organic-rich deep marine strata in order to aid the assessment of hydrocarbon source and reservoir rocks.

Theory and Methods

Modern deep-marine levees sequester a large proportion of the world's total buried organic carbon — currently ~ 20% of the global flux of buried carbon occurs in deep marine levee deposits of the modern Bengal fan (Galy et al., 2007; Baudin et al., 2017). However, few studies have attempted to assess this process in ancient deep-marine sedimentary rocks, or to appraise their potential as petroleum source or reservoir rocks. Deep-marine levees are areally extensive features that experience high sedimentation rates, making them ideal sites for significant organic carbon concentration, burial and preservation. However, levees have received little research attention compared to adjacent channels – an artefact of generally poor exposure in the ancient rock record and widely-spaced control points in the modern. Because of this observational bias many important features of levees remain to be fully documented.

At the Castle Creek study area in east-central B.C., Neoproterozoic Windermere Supergroup levee deposits are vertically dipping and exceptionally well exposed due to glacial polishing. This allows detailed observation at many scales and makes comprehensive examination and description of lithology and stratal geometry possible, which is critical to understanding and modelling depositional processes and reservoir geometry and continuity. Additionally, the mudstone-rich levee strata can be systematically sampled, and geochemically analysed, such as total organic carbon (TOC) and stable isotope analysis.

Results and Observations

At the Castle Creek study area, Neoproterozoic Windermere Supergroup levee deposits have total organic carbon (TOC) content between < 0.1% to 1.7%. These values are uncorrected for the effects of greenschist metamorphism and possible loss of ~50%-~80% of the original organic carbon content (Smith, 2009; Hayes et al., 1983), suggesting that depositional values may have been as high as ~7%. Organic-rich strata commonly occur as either organic-rich mudstone beds or as distinctive black clay-rich laminae in sand-rich turbidites (Figure 1). Sand-rich beds with these distinctive interlaminae are typically planar- or ripple cross-stratified and contain anomalously high intergranular porosity filled with carbonate cement. Scanning electron microscopy (SEM) shows that residual organic carbon occurs primarily as nano-scale coatings on clay particles, but also as uncommon sand-sized organomineralic aggregates and discrete sand-sized amorphous grains in sandstone beds. Much of 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 suspended organic carbon pool in the upper water column over the continental shelf and further offshore. This material then became physically adhered and/or chemically adsorbed onto the surface of clay minerals and subsequently was resedimented by suspension settling and advected by turbulent suspensions into the deep sea. Accumulation by suspension settling would have been slow and roughly uniform across the seafloor. However, in the case of advective transport, low-density organic material and fine-grained clay minerals would have been preferentially transported in the upper part of turbidity currents, and therefore more likely to overspill the channel margin and become concentrated in levee deposits, where they were rapidly buried due to high sedimentation rates, and therefore protected from extensive oxidative and microbial degradation.

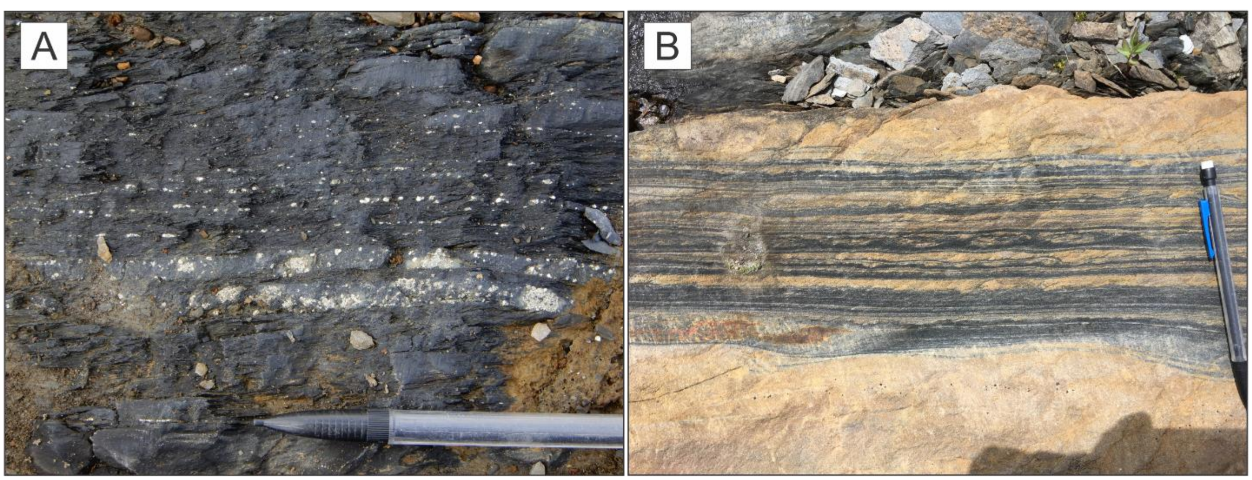

Figure 1. A) Organic-rich levee mudstone with abundant framboidal pyrite. B) Organic-rich, planar-stratified sandstone. Organic carbon is concentrated in the black laminae where it is closely associated with clay minerals.

Organic-rich clay laminae typically contain abundant framboidal pyrite and minor collophane (Figure 1). Interstratified sandstones contain up to 35% iron-rich cement, consisting mostly of ferroan dolomite and secondary ferroan calcite, with minor siderite (Figure 2). This mineral assemblage results from the progressive diagenesis of organic-rich strata. Framboidal pyrite formed first during bacterial sulphate reduction. With further burial, ferroan calcite and collophane crystallized subsequently. Diagenesis and dissolution of organic carbon to form kerogen combined with bacterial fermentation in the mudstones would have contributed both carbon to the cements and phosphorus to the collophane. The absence of sulphide would have allowed Fe^{2+}, in addition to Fe^{2+}, Mg^{2+}, and Ca^{2+} released from clay exchange reactions, to increase in pore water, eventually leading to the formation of ferroan dolomite and siderite cements accompanying bacterial fermentation and decarboxylation. During late-stage diagenesis and early-stage metamorphism the ferroan dolomite and siderite continued to form with cations supplied from clay-mineral transformations such as smectite-illite transformation, and from the dissolution and re-precipitation of previously formed calcite cements. Although sandstone interbeds would have had the highest effective primary porosity and permeability in the mudstone-dominated succession, the extensive early ferroan carbonate cementation prior to petroleum generation significantly reduced overall reservoir quality. Additionally, mechanical compaction of the adjacent organic-rich mudstones would have reduced their thickness by up to 50% and lowered their porosity by a factor of 6 (Khan et al., 2011).

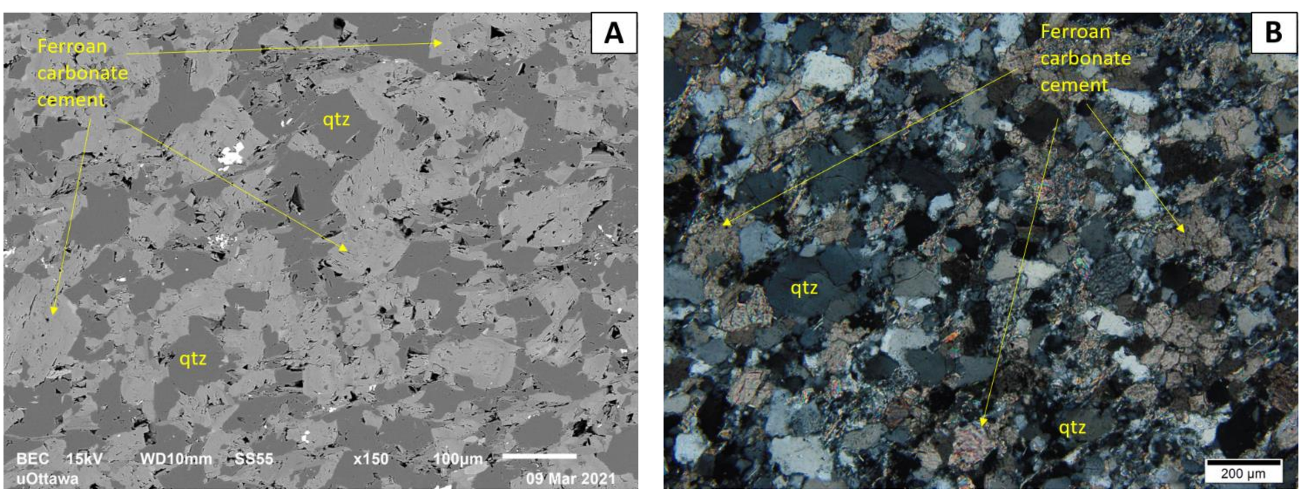

Figure 2. (A) Scanning electron microscope and (B) cross-polarized petrographic photomicrographs of fine-grained sandstone turbidites with abundant early diagenetic ferroan carbonate cement filling primary porosity. Note the open granular framework with

high intergranular volume indicating that cementation preceded significant mechanical compaction, and therefore is an early diagenetic phase.

Conclusions

Depositional processes in levees result in major concentration and enrichment of sedimentary marine organic matter. Depositional TOC values indicate the formation of rich potential petroleum source rocks in levee strata at the Castle Creek study area in B.C. When the significant thickness and wide geographic extent of these levee deposits are considered, they represent a significant organic carbon reservoir. In levee strata, organic matter can be sequestered either in mudstones or in interstratified sandstones and mudstones, where they occur primarily as nano-scale carbon films adsorbed onto clay mineral surfaces. A distinct diagenetic mineral assemblage is present in organic-rich strata that reflects the interplay of organic and inorganic diagenesis controlled by increasing burial depth and temperature. Studying the occurrence of organic-rich levee strata and their diagenetic history will improve our understanding of deep marine petroleum systems and the assessment of source rock and reservoir quality and richness in fine grained lithologies.

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