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Deconstructing Organic-Rich Mudrocks: Palaeoceanographic Considerations from the Exshaw Formation, Alberta, Canada

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The Exshaw Formation is one of the major source rocks of the Western Canada Sedimentary Basin. This mudrock sources of hydrocarbons of the enormous Cretaceous oil sands and heavy oil accumulations in north-eastern Alberta and west-central Saskatchewan. The Exshaw Formation is also a potential reservoir rock in south-eastern Alberta, where it forms a lateral western continuation of the prolific Bakken Formation in the Williston Basin to the east.

The Exshaw Formation is part of a regionally extensive continuum of Devonian-Mississippian organic-rich mudrocks overlying carbonate strata across western North America and beyond. These mudrocks encompass the Hangenberg Bio-event, a latest Devonian global extinction event that punctuated faunal and floral diversity. The origin of this globally extensive source rock forming period has been the subject of numerous studies and speculation and has raised important questions. Most notable questions include - why is this unit so rich in organic matter? What inhospitable conditions developed to shut-off the Upper Devonian carbonate-production factory? What oceanographic factors lead to the generation of such rich organic accumulations? Are there spatial and vertical contrasts of organic richness within the Exshaw? These questions are addressed in this presentation which examines multidisciplinary data obtained from key wells across the Alberta Basin and applies recent advancements in paleoceanography to interpret the genesis of this important organic-rich mudrock.

In this study a multidisciplinary approach integrating sedimentology, stratigraphy, ichnology, palaeontology, organic and inorganic geochemistry was undertaken in order to further understand the uniqueness of the Exshaw Formation and provide insight as the origin of a distinctive period in earth history. Inorganic geochemical techniques included the study of major, minor and trace elements by XRF techniques and mineralogy by XRD diffraction. Organic geochemical approaches included ROCK EVAL analysis, stable isotopes of carbon and nitrogen, Fourier Transform Infra-Red (FTIR) investigation of organic matter and organic petrographic analyses. Unsupervised geostatistical techniques (principal component analysis), elemental enrichment factors and correlation matrices were used to investigate a large geochemical dataset of 67 parameters from 6 key wells across the Alberta Basin. Results show three clusters of elements

reflecting different palaeoceanographic processes. Cluster I comprises Al, Ba, Co, Cr, Fe, K, Mg, Mn, Nb, Pb, Rb, Si, Ti, Y, and Zr, reflecting elements that are highly correlated to one another, appear genetically related and are interpreted as detrital-proxying elements. Cluster II comprises Mo, N, Ni, S, V, Zn and $\delta^{15}N_{total}$ which are related to redox- and productivity-proxying processes that are closely intertwined and are statistically indistinguishable. The third cluster comprises Ca, Mn, P and Sr, which are related to phosphatic nodules (phosphogenesis?) and/or phosphatic detritus.

The Exshaw mudrocks are divided into an organic-rich, laminated, black Facies B_1 and an overlying organic-lean, laminated Facies B_2. Facies B_1 exhibits rich, well-preserved organic matter with a median TOC value of 9.6 wt%, median Hydrogen Index (HI) value of 603 mgHC/gTOC and Type I/II organic matter. Facies B_2 exhibits organic-lean, poorly-preserved organic matter with a median TOC value of 1.9 wt%, median HI value of 349 mgHC/gTOC and Type II/III organic matter. Facies B_1 sharply overlies the Big Valley (part of the Wabamun Group) Upper Devonian carbonate platform accumulation.

Facies B_1 which has higher TOC, lighter $\delta^{15}N_{total}$, lower V/Mo, higher Mo/TOC, high EF_{Cu}, EF_{Ni} and lower Oxidation index (Ox.I. derived from FTIR) reflects active water mass circulation, lower water column ventilation, higher degrees of primary production and lower organic matter oxidation. Facies B_2 which has lower TOC, heavier $\delta^{15}N_{total}$, higher V/Mo, lower Mo/TOC, low EF_{Cu}, EF_{Ni} and higher Ox.I reflects limited circulation, higher water column ventilation, low degrees of primary production and higher organic matter oxidation. During Facies B_2 deposition lower amounts of organic matter generation reduced the demand for oxygen from the water column and promoted a low degree of ventilation in the water column for short periods of time.

The geochemistry, mineralogy and organic content of the mudrock facies is strongly correlated with palaeogeographic setting. Facies B_1 was deposited in the Peace River Embayment of north-eastern Alberta, connected to the open ocean to the west. The deposits reflect water column ventilation and high degrees of primary production generating high TOC, well-preserved organic matter, and high bio-element accumulations such as Cu and Ni. In contrast, Facies B_1 of south-eastern Alberta reflects lower water column ventilation and a greater proportion of recycled organic matter indicating limited contact to a nutrient-rich replenished water mass, and was deposited on the north-western rim of the Williston Basin, an epicontinental cratonic sag with limited communication to the open ocean to the west., Facies B_2 on the other hand reflects extreme isolation of sub-basins in shallower water settings that did not experience water column circulation or significant primary productivity processes, thus leading to lower TOC, more oxidation of organic matter and lower concentrations of the bioelements Cu, Ni and Zn. The inhibited water column circulation reflecting Facies B_2 occurred in conjunction with a eustatic sea-level fall at the Devonian-Carboniferous boundary. The sea-level fall promoted basins to become isolated , stagnant and exposed to limited water column circulation.

The Exshaw mudrocks exemplify the spatial complexity of active palaeoceanographic processes responsible for formation of source rocks and organic facies-specific variations. Understanding these complex processes provides insight that helps predict the distribution of source rock quality, quantity and type which ultimately affects the ability of this organic-rich mudrock to serve as both a prominent source rock and a reservoir rock.