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Research paper

A novel method to estimate mineral compositions of mudrocks: A case study for the Canadian unconventional petroleum systems

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ABSTRACT

The mineral composition of mudrocks is an essential attribute in controlling the reservoir quality of unconventional petroleum systems. The present study introduces a semi-quantitative method to estimate mineral phases of mudrocks in various Canadian unconventional hydrocarbon systems using total elemental analysis (inductively coupled plasma-mass spectrometry (ICP-MS)) and Rock-Eval data (total organic carbon (TOC) and mineral carbon (MinC)).

This method involves statistical analysis based on a sound knowledge of hydrocarbon source rock inorganic geochemistry. The workflow can be divided into four steps: (i) converting major elements (Si, Al, Fe, K, Na, Ca, Mg, Ti, and P) to their oxides, (ii) inferring modes of occurrence of elements using statistical analysis of geochemical data (major elements, TOC, and MinC), (iii) identifying the mineral types (oxide, aluminosilicates, carbonates, sulfide, and phosphate) according to elemental occurrences and calculating mineral phase concentrations, and (iv) verifying the results by comparing to XRD data on selected samples. The results, especially for brittle minerals such as quartz, carbonates (e.g. calcite, dolomite, and ankerite), and pyrite, show that the estimated mineral compositions correspond closely and consistently with measured mineralogy obtained from XRD. This method takes advantage of bulk geochemical data already available for hydrocarbon potential and chemostratigraphic studies, without devoting additional samples and cost for XRD analysis.

1. Introduction

The mineralogy of mudrocks in an unconventional petroleum system is regarded as one of the primary factors in controlling reservoir quality and is vigorously investigated for evaluation and exploitation of these resources (e.g. Ross and Bustin, 2008, 2009; Kondla et al., 2016). Brittle minerals (such as quartz and calcite) are critical for effective hydraulic fracturing (e.g. Wang and Gale, 2009; McCarty et al., 2015), while clay is associated with permeability-porosity of shale (Yang and Aplin, 1998; Gensterblum et al., 2015). Phosphate nodules have been shown to contribute to porosity and provide capacity for hydrocarbon storage within the rock (Kondla et al., 2016). X-ray diffraction (XRD) is the most widely used direct technique for qualitative and quantitative analysis of minerals in geological materials. Mineral components can also be indirectly evaluated by geophysical log data (Zorski et al., 2011; McCarty et al., 2015). The mineral compositions of mudrocks are mainly associated with the major elements and include Si, Al, Fe, K, Na, Ca, Mg, Ti, S, and P (Ward et al., 1999, 2001; Dai et al., 2012, 2014, 2015; McCarty et al., 2015).

Preliminary screening of well samples often includes bulk inorganic and organic geochemical analyses (e.g., inductively coupled plasma-mass spectrometry (ICP-MS) and Rock-Eval analysis), which are not only cost effective, but also fast and require a minimum quantity of samples. The results generate important information about the quality and quantity of organic carbon for assessment of hydrocarbon potential as well as the bulk concentrations of major and trace elements used for chemostratigraphy (Sanei et al., 2014; Haeri-Ardakani et al., 2015; Kondla et al., 2015). More detailed petrophysical analyses include quantitative

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mineralogy which requires more costly and material intensive XRD analysis.

This study presents a calculative process using correlation coefficients and cluster analysis for estimating the mineral phases and concentrations of mudrocks using existing screening bulk geochemical data (major elements, TOC, and MinC). The results, especially for brittle minerals such as quartz, carbonates (e.g. calcite, dolomite, and ankerite) and pyrite, agree well with those obtained from XRD semi-quantitative analysis. However, this method is an estimation and therefore, high numbers of samples should be used in order to improve statistical significance.

2. Geological setting

The Late Ordovician Lorraine and Utica shales of southern Quebec, the Early Jurassic Nordegg shale of Alberta, and the Middle Triassic Murray Harbour Formation mudstones from the Arctic Archipelago of Canada were investigated in this study (Fig. 1).

The Upper Ordovician Utica and Lorraine shales are found in southern Quebec between Montreal and Quebec City (Fig. 1). In Quebec, the Utica Shale consists primarily of mudstone with a high carbonates content (Lavoie, 2008; Lavoie et al., 2014). Extensive thermal maturation studies using various thermal maturity indicators (Tmax; organic matter reflectance) show that the Utica Shale is a mature succession with an increase in maturation towards the southwest from oil window-condensate zone in the Quebec City area to the dry gas zone (Haeri-Ardakani et al., 2015). Higher calcite content, fine-grained limestone beds and scarcity of siltstone and sandstone beds in comparison to overlying Lorraine Group suggest that it was deposited prior to the influx of coarser sediments coming from erosion of the Appalachian thrust sheets (Lavoie et al., 2014). The calcareous shales of the Utica shale accumulated due to a rapid increase in sea level, whereas the carbonate producing zone was partially shut down leaving siliciclastic muds with subordinate carbonates mud to accumulate (Globensky, 1987). However, abundant occurrences of graptolites, brachiopods, trilobites and cephalopods suggest a lack of anoxic conditions in the depositional basin (Lavoie et al., 2014). The Utica Shale is characteristic of early flysch-phase fill along the distal flank of the Middle to Late Ordovician Taconian foreland basin (Bradley and Kidd, 1991).

The Lorraine Group conformably overlies the Utica Shale and is a flysch succession dominated by mudstones and siltstones with local thicker bedded sandstones. It consists of syn-orogenic sediments accumulated during the Late Ordovician. The siliciclastic sediment sources were derived from thrust sheets located to the southeast (Hisscott, 1995; Comeau et al., 2004). The Lorraine Group consists of interbedded calcareous shales and fine-grained turbidite sandstones with thin layers of limestone or calcareous sandstone occurring at approximately 3 m intervals. The fine-grained sandstone layers are thinly bedded and exhibit cross-laminations.

The Early Jurassic Nordegg shale is a member of the Fernie Formation and is one of the richest oil-prone source rocks in the Western Canada sedimentary basin. It is speculated to have generated significant amounts of oil, some of which is interpreted to have sourced Triassic, Permian, and Cretaceous reservoir units, and most of the oil is believed to still be trapped within the Nordegg (Creaney and Allan, 1990; Riediger et al., 1990; Riediger, 1994). The thickness of the Nordegg ranges from up to 50 m near the eastern sub crop margin to 20 m in the west (Asgar-Deen et al., 2004). It consists of fine-grained, laminated, organic-rich, fossiliferous, phosphatic, argillaceous, siliceous, and calcareous mudstones, consistent with a shelf ramp facies (Asgar-Deen et al., 2003, 2004).

The Middle Triassic Cape Caledonia Member of the Murray

Fig. 1. Map of Canada showing locations of (1) the Lorraine and Utica shales, (2) Nordegg shale, and (3) Cape Caledonia Member mudstone.