Clay composition and diagenesis in the organic-rich Upper Devonian Duvernay Shale, Western Canadian Sedimentary Basin

Hui Li[1], Nina Zeyen[1], Nicholas B. Harris[1]

[1] Department of Earth and Atmospheric Science, University, Edmonton, AB T6G 2E3, Canada

Introduction

Clay minerals are major components in organic-rich shale. In some mudstones, mixed-layer clays, in which illite and smectite are interstratified at a crystallographic scale, are common components. Smectite layers within mixed-layer clays can convert to illite layers under certain conditions, a mineralogical reaction that influences reservoir and geomechanical properties of the mudstone and nearby formation (Boles, 1979). In addition, the reaction extent can be used to reconstruct the thermal and tectonic histories (Clauer and Lerman, 2012).

The classic model for smectite to illite conversation derives from studies of Tertiary sediments of the Gulf Coast, in which the proportion of illite in mixed layer I/S increases from less than 20% (1850m and shallower) to about 80% (3700m and deeper) (Hower er al., 1976). This transition is associated with parallel changes in the diagenetic mineralogy of the mudstones, including dissolution of detrital K-feldspar, and formation of albite, quartz, ferrous carbonate, and chlorite cements. However, clay compositions in the Duvernay Formation shows different characteristics than the classic diagenetic transitions. From 1100 to 4000 m in Duvernay Formation, corresponding to immaturity to dry gas window respectively, discrete smectite is never present, even in the shallowest, lowest maturity samples, and highly illite-rich I-S mixed layer clays are dominant. It is still a question why the S-I reaction does not follow the classical model of the Gulf Coast. After examination of the clay minerals in the Duvernay Formation, we suggest that other models describe the clay mineral assemblage in this formation, including smectite conversion to illite catalyzed by biotic processes, either in soil zones before transport to and or by microbially-mediated iron reduction in anomalously shallow burial depth. Either model would predict the clay compositions in the Duvernay Formation.

Method

Core samples were selected from 5 wells in the Duvernay shale (Fig. 1). The sample depths range from 1116.63m to 3974.54 m, covering the thermal maturity from immaturity to dry gas window. Marine-derived Type Ⅱ organic matter is the dominant type in the Duvernay Formation, which has a TOC content of 0.1-11.1% (Harris et al., 2018). The cores were characterized for geochemistry properties (Harris et al.,2018). Samples consisted of 10 cm long slabs cut from the back of cores that were subsequently split vertically into aliquots for multiple analyses.

Bulk samples and separated clay size fraction were analyzed by X-Ray diffraction method to determine mineral content. Both sample types were analyzed in the range 3-80° 2θ in a Bruker D8 Advance diffractometer, using a Cobalt anode. To further determine the presence of smectite, samples were analyzed in 2 different conditions. For the bulk samples, the analyses were performed in both an air-dry state and a cation-exchanged state, in which samples were immersed in CaCl2·H2O solution overnight. For the clay-fraction samples, the analyses were performed in both air-dry and following overnight glycolation at 50℃ in a glycol atmosphere.

Samples were polished for SEM observation to identify the composition, shape and occurrence of minerals. The imaging was performed by a Zeiss Sigma field emission scanning electron microscope (FESEM) configured with backscatter (BSD) detector, and an energy dispersive X-ray spectroscopy (EDS) system. An accelerating voltage of 15 kV and a working distance of 8.5 mm will be used to acquire quality images.

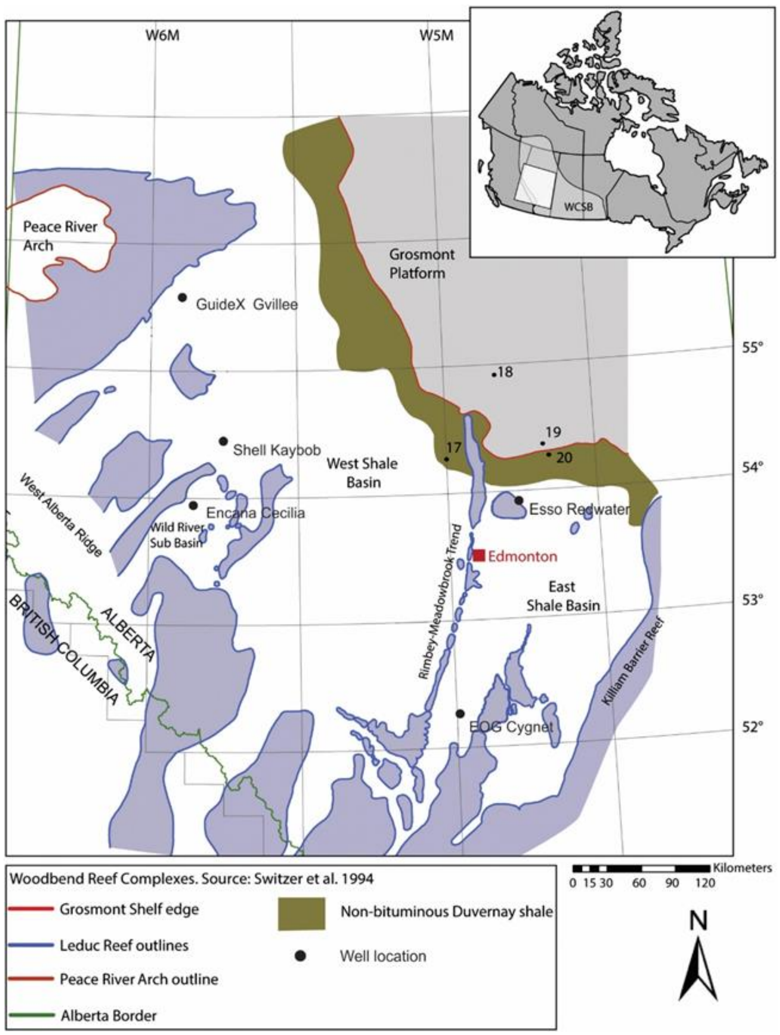

Fig. 1. Location map showing geographic distribution of the wells in this study (Modified from Harris et al., 2018)

Results

The Duvernay shale consist mainly of quartz, feldspar, calcite, dolomite, pyrite, highly illitic mixed -layer I/S or illite, muscovite and chlorite. There are higher quartz, K-feldspar and clay contents and lower calcite content in samples from the West Shale Basin than in the East Shale Basin. The contents of plagioclase and mica is slightly elevated in the West Shale Basin samples. The concentrations of minor phases, including dolomite, ankerite and pyrite, are not systematically different between the two areas. The fine fraction of this shale consists of a slightly expandable illite-rich mixed layer I/S verified by the absence of 17 Å peak and slight collapse on the left side of 10Å peak (Fig. 2).

SEM images show that the clay-size particles (＜2μm) are a K-rich clay mineral that is identified as illite. The illite has two morphologies, a fibrous type that fills interparticle pores and a platy type that is distributed parallel to the edges of detrital particles. Detrital K-feldspars are present over the range of depth and albite, ankerite and Fe-dolomite appear and increase gradually with increasing depth.

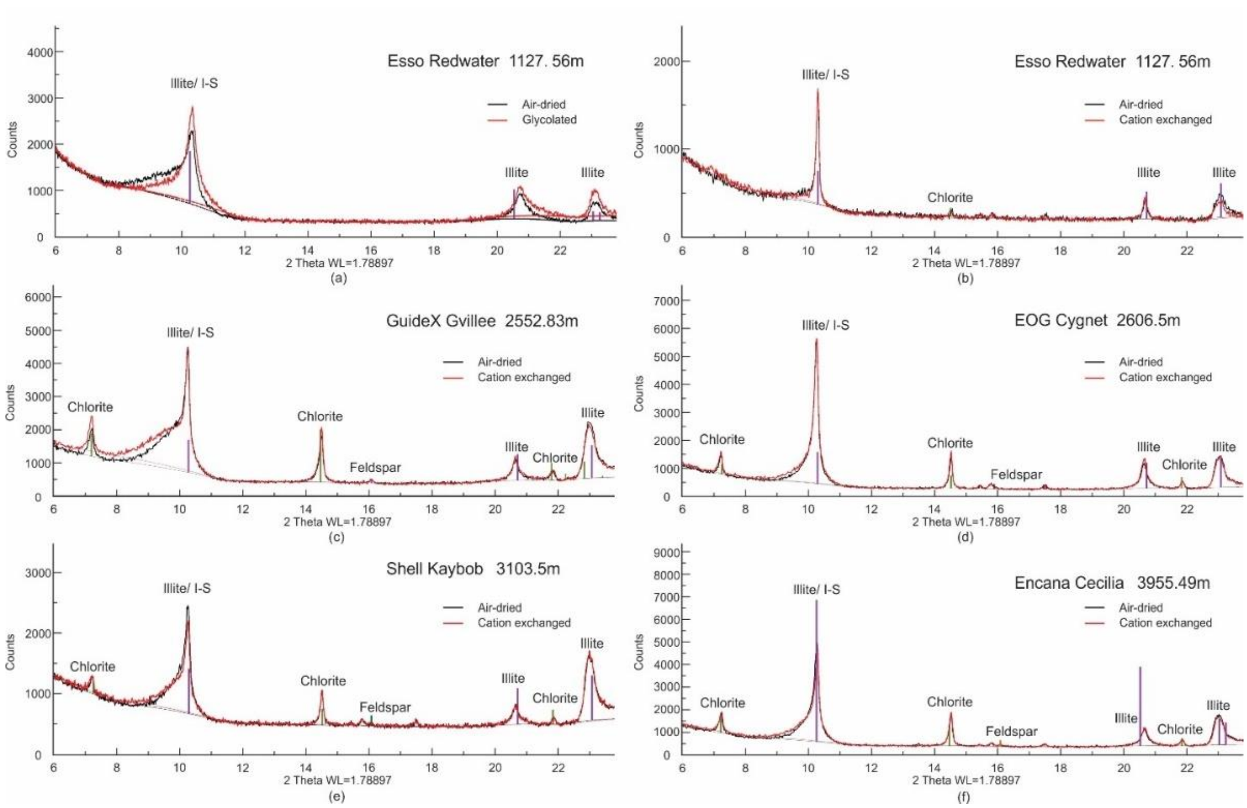

Fig. 2. X-ray diffraction patterns of air-dried (black), ethylene glycol-saturated or cation exchanged (red) fine clay fractions of shales from different depths. Smectite is absence. I/S, illite–smectite.

Discussions

Based on the classical S-I reaction model of the Gulf Coast, the mixed-layer clay at the shallow burial depth and low thermal maturity should be smectite-rich with high expandability. Instead, we observe low expandability, highly illitic mixed-layer clay in low thermal maturity samples, suggesting that mixed-layer smectitic clays may have never entered the basin during Duvernay deposition or, alternatively, different models for smectite-to-illite conversion should be adopted for these rocks.

If the smectite never entered the basin, the illite could have been detrital, either derived from weathering of bedrock or possibly from discrete muscovite. The Canadian Shield and a northern source of sediments could have provided siliciclastic and detrital illite for the Duvernay Formation. However, the fibrous and platy form of illite observed in SEM analysis indicates an authigenic or diagenetic mixed layer origin. Dissolved K-feldspar and gradually increasing albite and Fe-rich carbonate suggests that the S-I reaction occurred at a shallow depth in the Duvernay Formation. There are 2 potential models driven by biotic factors:

(1) The smectite-rich mixed clay converted to illite before burial. This could have occurred in a soil horizon during seasonal wetting (reducing) and drying (oxidizing) cycles that help bacteria to drive Fe^{3+} reduction in clay structure, leading to increased layer charge and coupled K fixation, and facilitating the smectite to illite transition (Huggett and Cuadros, 2005). The example in Solent Group was buried less than a few hundred meters and clay is primarily composed by illite or illite-rich mixed layer (Huggett and Cuadros, 2005), which is similar to the clay assemblages in the Duvernay Formation.

(2) The I-S conversion took place at relatively shallow depths through the microbially induced reduction of phyllosilicate structural Fe (III). Kim et al. (2019) present evidence for a naturally occurring microbially induced S-I transition within 500-700m burial depth range, via biotic reduction of structural Fe (III) in phyllosilicates. The Duvernay shale is organic-rich with abundant Type II organic matter, which suggest the potential of shallow generated methane. The coupled oxidation of methane and reduction of structural Fe (III) provide the possibility of I-S conversion at shallow depth.

Conclusions

The presence of low expandability, illite-rich mixed layer clay in the Duvernay Formation at shallow depth, corresponding to low thermal maturity, demonstrates that the S-I transition follows a different pathway from the classic model in which elevated temperature is the primary driver. If the clay diagenetic process is facilitated by biotic activities and smectite converts to illite at a shallower burial depth than in the classic model, reservoir quality of the formation is affected by smectite-illite conversion in shallower and less compacted areas. In addition, the formation of illite does not reflect maturity or burial depth.

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