Clay composition and origins of the Devonian Duvernay shale, Western Canadian Basin, Canada

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

[1] Department of Earth and Atmospheric Sciences, University of Alberta

Summary

The Upper Devonian Duvernay Formation in the Western Canada Sedimentary Basin is a prolific shale reservoir and the source of much of the oil found in convention Lower Paleozoic reservoir. Clay minerals in this and other shale reservoir formations are significant to petrophysical and geomechanical properties, and mineral reactions affect development strategies. Despite their importance, the clay mineralogy of black shales in general, and the Duvernay Formation specifically, is poorly understood. One important mineralogical reaction is the transformation of mixed layer clays from smectitic (expandable) to illite (non-expandable) compositions.

We have applied X-ray diffraction (XRD) analysis to 29 Duvernay shale samples from 5 wells representing a range of thermal maturities from immature to dry gas window. Existing models based on Gulf of Mexico mudstones for the smectite to illite transition suggest that immature samples should be smectite-rich, and the transition to illite-rich compositions should take place in oil-window samples. However, in Duvernay samples from depths as shallow as 1100m with the low thermal maturity to depths of 3900 m with the high thermal maturity, the dominant clay is a highly illitic mixed layer clay, in contrast to the Gulf of Mexico models (Hower et al., 1976). Three models may explain the contrasting behavior of the Duvernay Formation: (1) only illite clay appeared in the source of clastic sediments; (2) the highly smectite mixed-layer clays converted to highly illitic clays before burial or (3) the conversion of smectitic to illitic mixed layer clay was catalyzed by microbially mediated iron, which help the reaction take place at low temperatures.

Method

Twenty-nine core samples were selected from 5 wells representing a range of thermal maturities (Fig. 1), burial depths and rock compositions: Esso Redwater (average Tmax=422˚C), GuideX Gvillee (average Tmax=444˚C), EOG Cygnet (average Tmax=448˚C), Shell Kaybob (average Tmax=471 ˚C), and Encana Cecilia (average Tmax=394˚C, which is uninterpretable due to the great burial depth and low S2 values) for multiple analyses. These cores were previously analyzed for TOC, Rock-Eval pyrolysis and abundances of major, minor and trace elements (Dong et al., 2018, 2019; Harris et al., 2018).

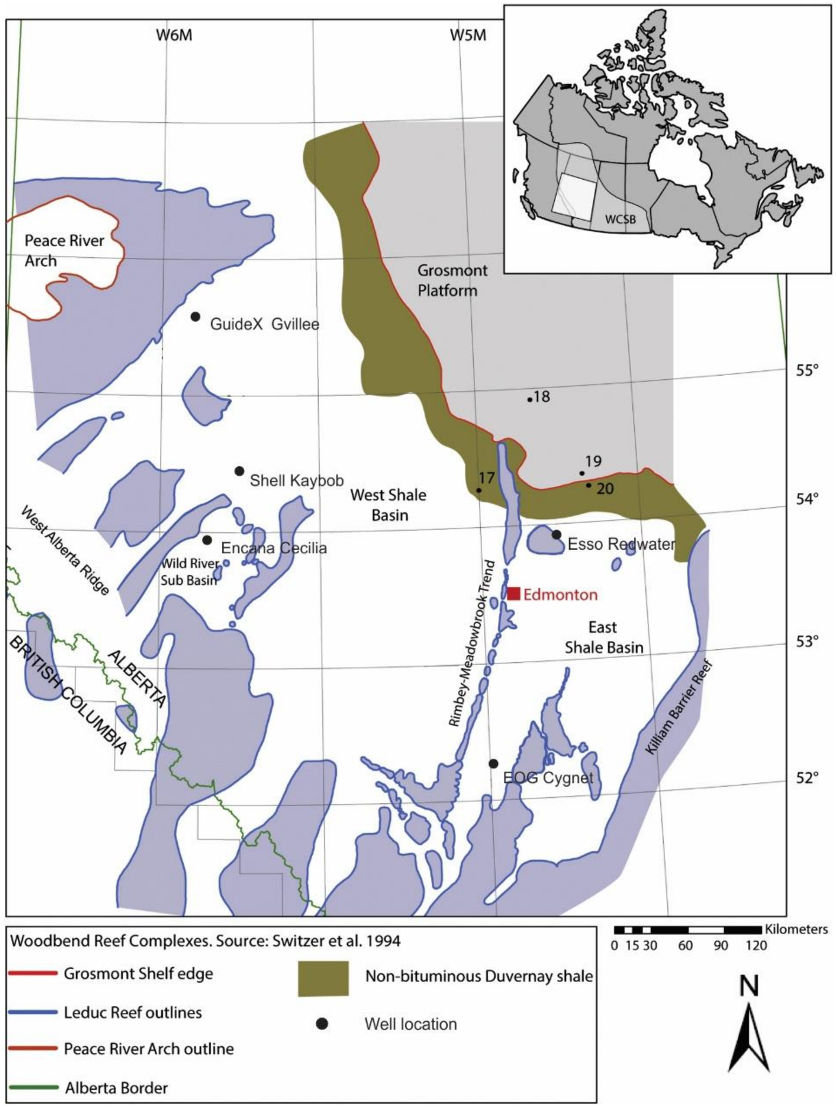

Figure 1 Map of study area and well locations (modified from Harris et al., 2018).

One spilt of core samples was crushed and micronized into fine powders and half of powders were immersed in 1M $CaCl_2$ solution overnight for the cation exchange process. X-ray diffraction analysis was performed both on those powders with and without cation exchange process to examine the expansibility of clays. The separated clay-size fraction (<2μm) from 5 samples was scanned for both after air-drying and after glycolation to further determine the expansibility.

Results and Discussion

The major mineral constituents of the Duvernay samples are quartz, plagioclase, K-feldspar, mica, calcite, dolomite, ankerite, clays, and pyrite. In East Shale Basin, including Esso Redwater and EOG Cygnet well, the content of carbonate in the sample is relatively high, and the contents of quartz and clay are relatively low, which is on the contrary of that in West Shale Basin. The contents of other minerals are similar in the East and West Shale Basins (Harris et al., 2018).

The clay assemblage consists mainly of highly illitic mixed-layer clays in all wells, with lesser amounts of chlorite and minor kaolinite (Fig. 2). Thus, there is no evidence for expandible smectitic mixed-layer clays, even at low thermal maturity samples nor is there evidence for any clay mineral transformation from shallow, low maturity samples to deep high maturity ones. In all case, the expansibility is very low or nonexistent.

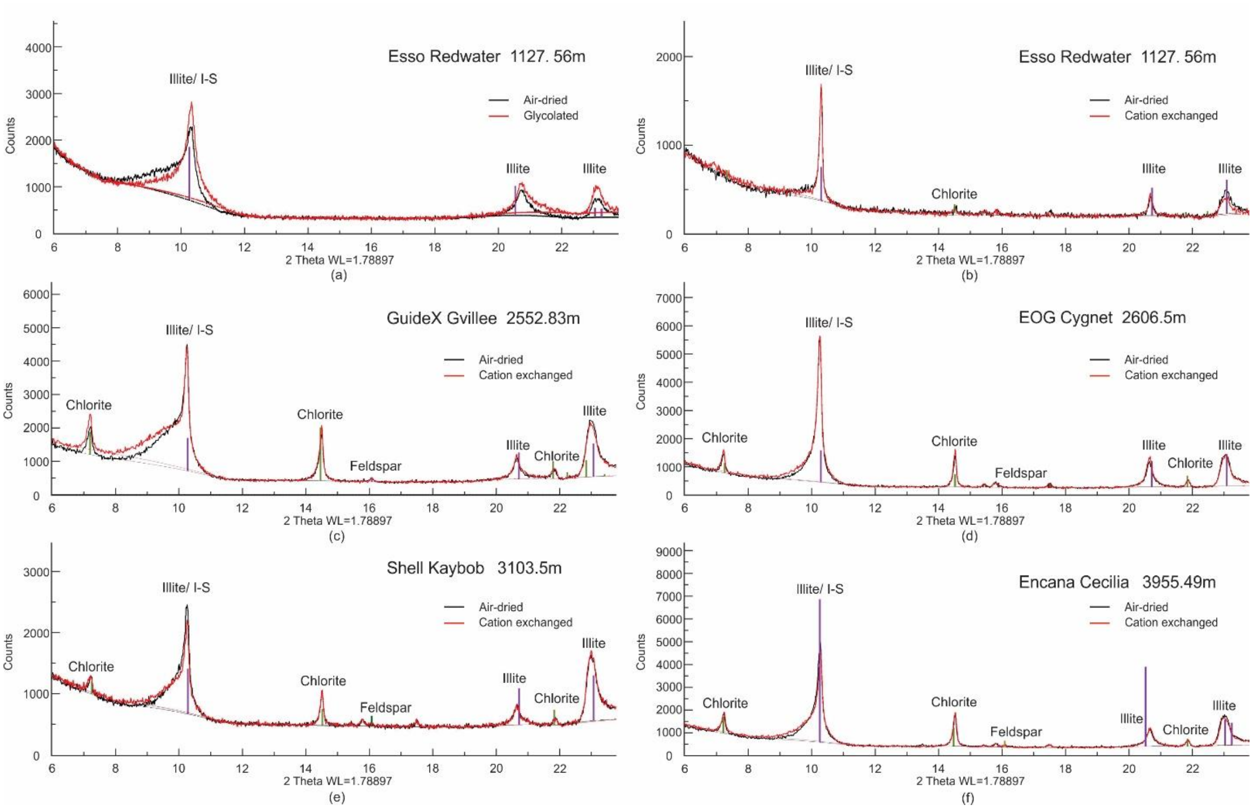

Figure 2 X-ray diffractograms of clay separates and whole rock of five representative samples. (a) clay separate, 1127.56m, Esso Redwater, (b) whole rock sample, 1127.56m, Esso Redwater, (c) whole rock sample, 2552.83m, GuideX Gvillee, (d) whole rock sample, 2606.5m, EOG Cygnet, (e) whole rock sample, 3103.5m, Shell Kaybob, and (f) whole rock sample, 3955.49m, Encana Cecilia.

The results obtained from the Duvernay are strikingly different from models for clay transformation developed for the Gulf of Mexico (Hower et al., 1976; Freed and Peacor, 1989; Lynch 1997), where at low thermal maturity, mixed layer clays show highly smectitic, high expansibility compositions. In addition, Gulf of Mexico mudstones typically show deep, high maturity development of chlorite, the iron in which has been interpreted as the conversion of smectite clays. The absence of a smectitic component even in shallow, low maturity Duvernay samples suggests that the smectite may not present in the sediment source, or the conversion took place before burial, possibly driven by alternating seasonal wet-day cycles in the source terrane (Huggett and Cuadros, 2005). Alternatively, there may have been another pathway for smectite converting to illite, such as catalysis by microbially Fe(Ⅲ) (Kim et al., 2019).

Conclusions

Our data indicate that in the Duvernay Formation and, possibly, other black shales, the formation of illite does not reflect maturity or burial depth. Illite formation may have nothing to do with diagenesis but simply reflect provenance. Alternatively, if conversion of smectite to illite is involved, a new low-temperature pathway is indicated, in which case reservoir quality of the formation is affected by smectite-illite conversion in shallower and less compacted areas.

References

Dong, T., Harris, N.B., Knapp, L.J., McMillan, J.M. and Bish, D.L., 2018. The effect of thermal maturity on geomechanical properties in shale reservoirs: An example from the Upper Devonian Duvernay Formation, Western Canada Sedimentary Basin. Marine and Petroleum Geology, 97, pp.137-153.

Dong, T., Harris, N.B., McMillan, J.M., Twemlow, C.E., Nassichuk, B.R. and Bish, D.L., 2019. A model for porosity evolution in shale reservoirs: An example from the Upper Devonian Duvernay Formation, Western Canada Sedimentary Basin. AAPG Bulletin, 103(5), pp.1017-1044.

Freed, R.L. and Peacor, D.R., 1989. Variability in temperature of the smectite/illite reaction in Gulf Coast sediments. Clay Minerals, 24(2), pp.171-180.

Harris, N.B., McMillan, J.M., Knapp, L.J. and Mastalerz, M., 2018. Organic matter accumulation in the Upper Devonian Duvernay Formation, Western Canada Sedimentary Basin, from sequence stratigraphic analysis and geochemical proxies. Sedimentary Geology, 376, pp.185-203.

Hower, J., Eslinger, E.V., Hower, M.E. and Perry, E.A., 1976. Mechanism of burial metamorphism of argillaceous sediment: 1. Mineralogical and chemical evidence. Geological Society of America Bulletin, 87(5), pp.725-737.

Huggett, J.M. and Cuadros, J., 2005. Low-temperature illitization of smectite in the late Eocene and early Oligocene of the Isle of Wight (Hampshire basin), UK. American Mineralogist, 90(7), pp.1192-1202.

Kim, J., Dong, H., Yang, K., Park, H., Elliott, W.C., Spivack, A., Koo, T.H., Kim, G., Morono, Y., Henkel, S. and Inagaki, F., 2019. Naturally occurring, microbially induced smectite-to-illite reaction. Geology, 47(6), pp.535-539.

Lynch, F.L., 1997. Frio shale mineralogy and the stoichiometry of the smectite-to-illite reaction: the most important reaction in clastic sedimentary diagenesis. Clays and Clay Minerals, 45(5), pp.618-631.