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HYDRODYNAMIC BACKGROUND OF THE ATHABASCA BASIN, SASKATCHEWAN, AND ITS CONTROL ON BASIN-SCALE GEOCHEMISTRY AND URANIUM MINERALIZATION

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1. Introduction

The Athabasca basin is known for its rich uranium deposits that are located at or near the unconformity between the Proterozoic siliciclastic rocks and Archean to Paleoproterozoic basement rocks. The formation of such deposits requires the circulation of enormous volumes of saline fluids, most of which are interpreted to be basinal brines (e.g. Hoeve and Sibbald, 1978; Wallis et al., 1983; Wilson and Kyser, 1987; Kyser et al., 2000; Jefferson et al., 2007; Mercadier et al., 2012). Therefore, it is important to understand the background hydrodynamic conditions of the Athabasca basin, in order to decipher the mechanisms of fluid flow responsible for uranium mineralization.

In this study, we document numerical modeling results of fluid pressure in the basin (including those related to sediment compaction and hydrocarbon generation) and fluid convection patterns due to geothermal gradients. The fluid flow modeling results are further used to interpret some geochemical patterns observed in sedimentary rocks of the Athabasca basin.

2. Geologic setting

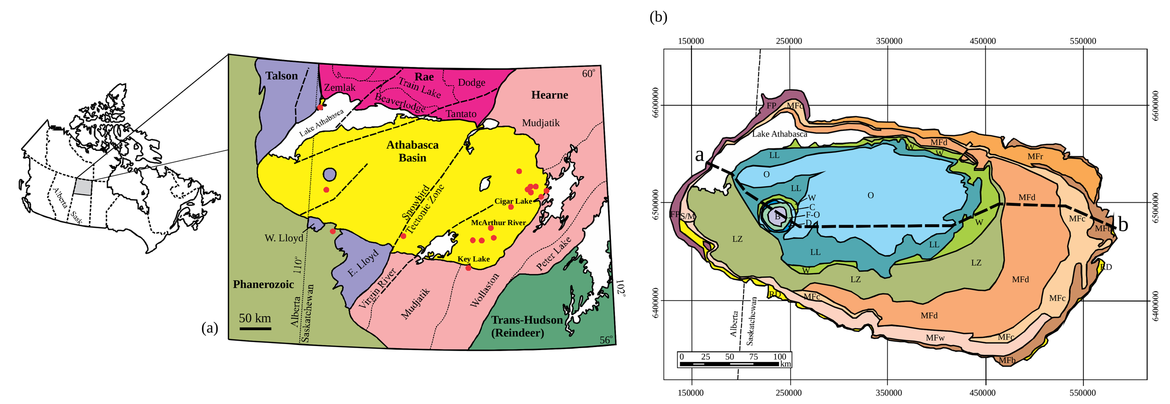

Fig. 1. (a) Location and regional geologic framework of the Athabasca basin (modified from Card et al., 2007); (b) Geological map of the Athabasca basin (modified from Ramaekers et al., 2007). Dashed line a–b indicates the location of the cross section shown in Fig. 2.

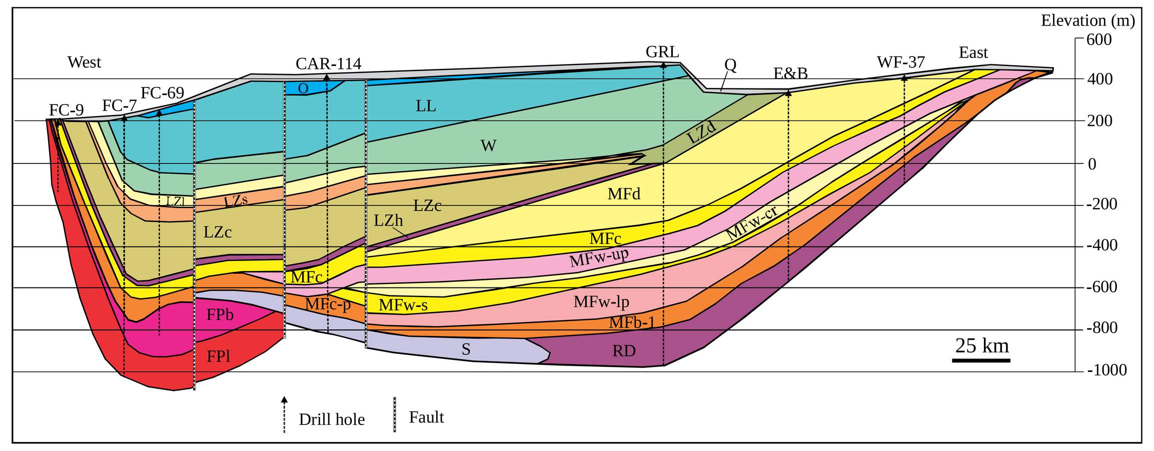

Fig. 2. East-West cross section of the Athabasca basin (modified from Ramaekers et al., 2007), with location shown in Fig. 1. FP — Fair Point; S — Smart; RD — Read; MF — Manitou Falls; LZ — Lazenby Lake; W— Wolverine Point; LL — Locker Lake; O — Otherside; D — Douglas; C — Carswell; Q — Quaternary.

3. Fluid pressure regime

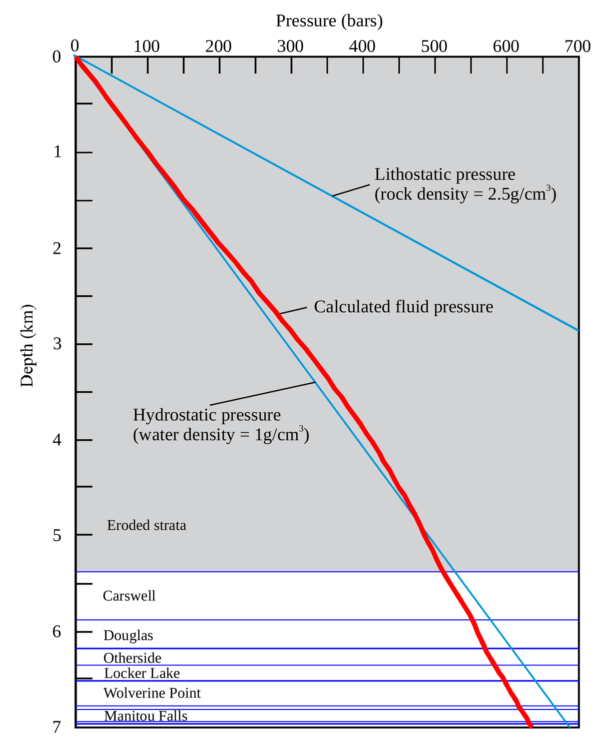

Fig. 3. Numerical modeling results showing the fluid pressure–depth profile in the central part of the basin at the end of sedimentation (includes ca. 5 km of eroded strata; modified from Chi et al., 2013).

As shown in Fig. 3, results of numerical modeling on the development of fluid overpressure due to disequilibrium sediment compaction suggest that no significant fluid overpressure was developed in the basin during sedimentation, ca. 1740 – 1541 Ma (Rainbird et al., 2007; Creaser and Stasiuk, 2007). Fluid flow related to sediment compaction was very slow and the temperature profile was undisturbed, implying that if compaction-driven flow was responsible for mineralization, the sites of mineralization would not record thermal anomalies (Chi et al., 2013).

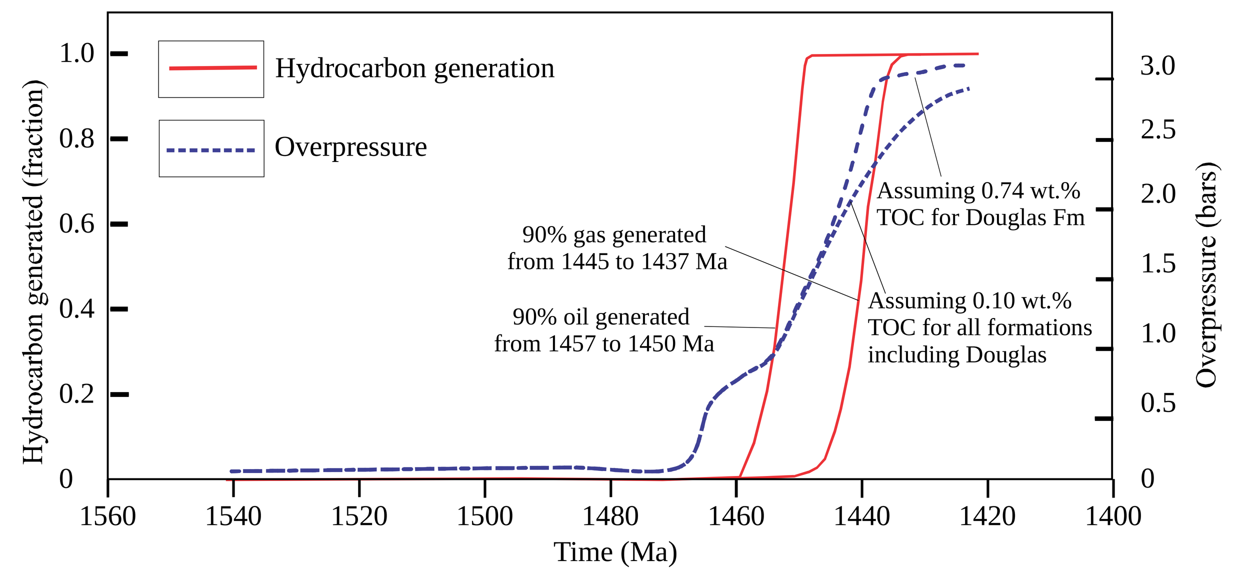

Fig. 4. Numerical modeling results showing the time intervals of oil and gas generation in the Douglas Formation in the basin centre, and the evolution of fluid overpressure in the basin centre, as compared to a model with 0.1 wt.% TOC (modified from Chi et al., 2014).

It has been shown that some of the hydrocarbons in the uranium deposits were derived from the Douglas Formation (Wilson et al., 2007). Numerical modeling involving hydrocarbon generation (Fig. 4) aims to evaluate how oil and gas generation processes in the Douglas Formation, which contains total organic carbon (TOC) of up to 3.56 wt.%, may have affected fluid overpressure development in the basin. As reported in Chi et al., (2014), if moderate permeabilities are used in the modeling for each lithology (known as the base model), oil and gas generation processes contribute little to the development of fluid overpressure, and fluid pressure in the basin is close to hydrostatic regardless of whether or not hydrocarbon generation in the Douglas Formation is included in the modeling. However, if permeabilities are assigned values one order of magnitude lower than in the base model, significant fluid overpressures are developed in the eroded strata in the upper part of the model. In the base model, oil generated in the Douglas Formation may migrate downward, driven by an overpressure zone situated above the Douglas Formation, but gas migrates upward. In the low-permeability model, however, the overpressures developed above the Douglas Formation are so high that both oil and gas generated in the Douglas Formation migrate downward. The numerical modeling results thus indicate that it is hydrodynamically possible for oil and gas generated in the ca. 1541 Ma Douglas Formation to migrate to the base of the basin and reach the sites of the unconformity-related uranium deposits that formed at ca. 1600 - 1500 Ma and 1460 - 1350 Ma, with significant remobilization events at ca. 1176 Ma, 900 Ma, and 300 Ma (Hoeve and Quirt, 1984; Cumming and Krstic 1992; McGill et al., 1993; Fayek et al., 2002; Alexandre et al., 2003; Jefferson et al., 2007; Creaser and Stasiuk, 2007).

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4. Fluid convection due to geothermal gradient

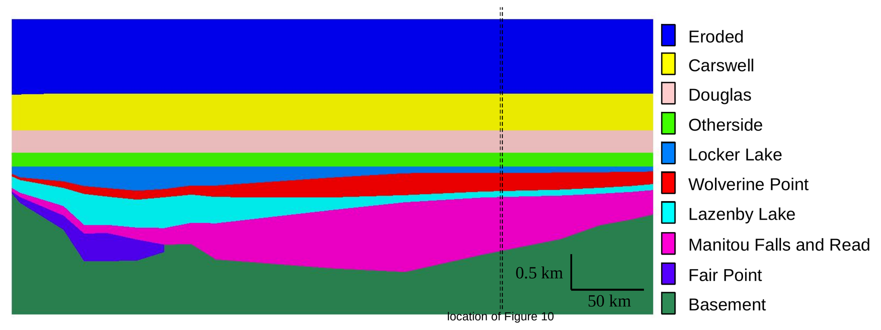

Fig. 5. Sectional view of the geometric model for numerical modeling derived from Fig. 2. Dash lines show the location of Figure 6.

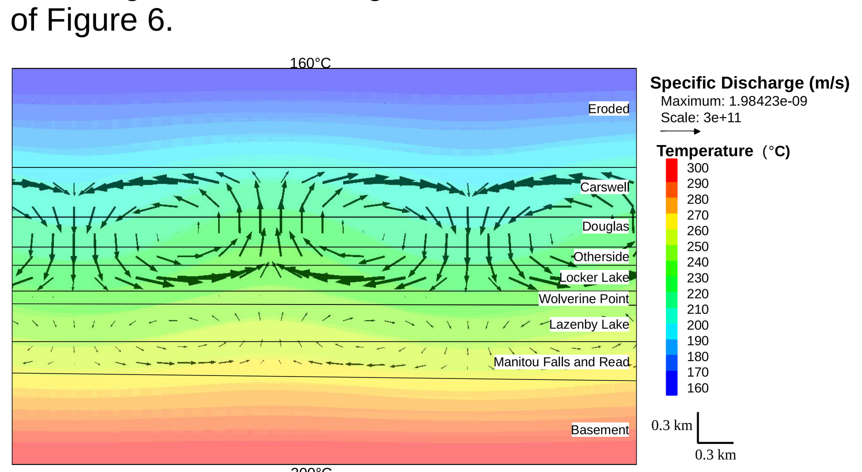

Fig. 6. Modelling results showing part of the basin (area outlined by the dash lines in Fig. 5). Temperatures are indicated by colour-coded isotherms. Fluid-flow patterns are shown by streamlines, with arrows indicating fluid-flow directions and the size of the arrows reflecting intensity of fluid flow.

Numerical experiments suggest thermal convection cells may have developed in the lower part of the basin, particularly below the Wolverine Point Formation, as well as in the upper part of the basin (if high permeability lithologies are assumed for the strata now eroded) at geothermal gradients of 25 to 35 °C/km. The results suggest that the largest convection cells formed above the 1644 ± 13 Ma Wolverine Point Formation, i.e. possibly post-dating the primary uranium event that predated 1630 ± 9 Ma (Davis et al., 2011). Changes to the assumed geothermal gradient do not modify the fluid flow patterns at the basin scale.

5. Geochemical characteristics of sedimentary rocks and relation to fluid flow

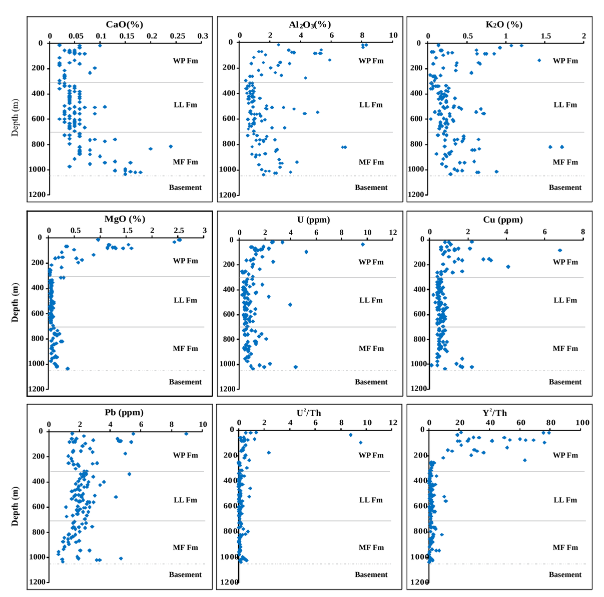

Fig. 7. Diagrams showing variation of CaO, Al_2O_3, K_2O, MgO, U, Cu, Pb, U^2/Th and Y^2/Th with depth of drill core DV10-001 (Bosman and Card, 2012). Formation contacts are also shown (modified from Chu et al., 2015).

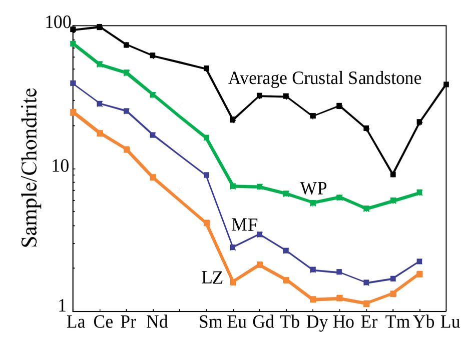

Fig. 8. Chondrite-normalized REE distribution patterns of samples from different formations of drill core DV10-001 (Modified from Chu et al., 2015). REE distribution pattern of average crustal sandstone is also presented for comparison (Turekian and Wedepohl, 1961).

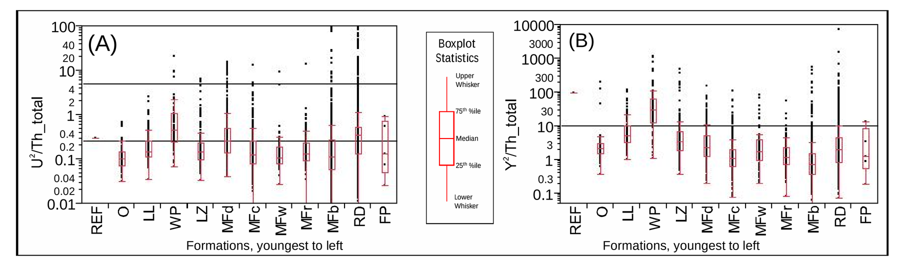

Fig. 9. Both enrichment of uranium relative to thorium (A) and hydrothermal alteration indicated by high Y^2/Th values (B) are observed in the Wolverine Point Formation, as indicated by the mean and median values (Wright and Potter, 2014).

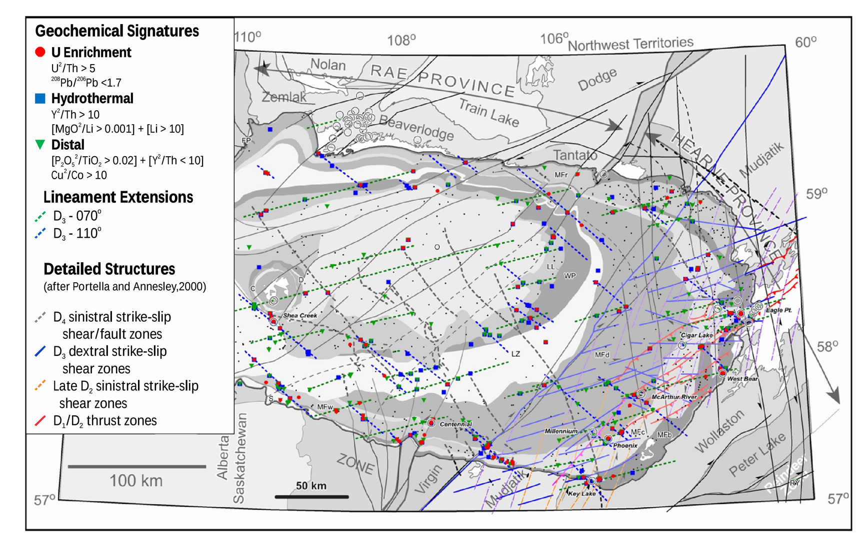

Fig. 10. Regional geochemical signatures interpreted from siliciclastic units of the Athabasca Group (Wright and Potter, 2014 and references therein).

The overall decrease in U, Cu, Pb and REE concentrations from the Wolverine Point Formation to the Lazenby Lake and Manitou Falls Formations (Figs. 7 and 8) probably reflect that more of these elements have been leached from the lower part of the basin (Chu et al., 2015). A distinct but locally stratabound hydrothermal signature (U^2/Th and Y^2/Th) in the Wolverine Point Formation (Figs. 7, 9 and 10) is here interpreted as broadly contemporaneous with and possibly genetically related to focused, primary uranium deposition elsewhere in the Athabasca Basin (Wright and Potter, 2014).

6. Summary

It is demonstrated that the fluid pressure remained near hydrostatic values throughout the deposition history of the basin, and that thermal convection cells may have been well developed in the lower part of the basin, particularly below the Wolverine Point Formation, as well as in the upper part of the basin (if high permeability is assumed for the strata now eroded).

These results, when compared with basin-wide geochemical data that indicate significant differences in chemical compositions between the Wolverine Point Formation and the underlying strata, suggest that the highly permeable lower part of the Athabasca basin experienced extensive chemical changes due to large-scale fluid circulation, which may have provided some of the chemical components found in the ore-forming fluids in the uranium deposits, including uranium and calcium.

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