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Numerical modeling of hydrocarbon generation in the Douglas Formation of the Athabasca basin (Canada) and implications for unconformity-related uranium mineralization

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ABSTRACT

The Proterozoic Athabasca Basin in Canada is known for its world-class, high-grade uranium deposits developed near the unconformity between the basin and the basement. The Douglas Formation in the upper part of the preserved strata in the basin contains total organic carbon (TOC) of up to 3.56 wt.%. Previous studies of organic matter maturation and hydrocarbon inclusions indicate that oil and gas have been generated from this formation, and that some hydrocarbons found in the unconformity-related uranium deposits were derived from the Douglas Formation. This study aims to evaluate how the oil and gas generation processes may have affected the fluid overpressure development in the basin, and whether or not the hydrocarbons generated in the Douglas Formation could migrate downward to stratigraphically lower intervals and eventually to the sites of mineralization near the unconformities. We carried out a series of numerical experiments to examine fluid overpressures, flow directions, temperatures, and oil and gas generation processes using a two-dimensional conceptual model derived from a geologic cross-section from the basin center to the eastern margin. An additional 5 km strata were added to current basin stratigraphy to account for observed paleogeothermal data. Variation studies were undertaken to account for uncertainties in the lithologies of the eroded strata, and the wide ranges of possible permeabilities of different lithologies and kinetic parameters of oil and gas generation. It is found that, 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 Douglas Formation to migrate to the base of the basin and reach the sites of the unconformity-related uranium deposits.

1. Introduction

The formation of the world-class, high-grade uranium deposits related to the Early Proterozoic Athabasca basin in northern Saskatchewan, Canada requires that large amounts of fluids flowed through the sites of mineralization. It is generally agreed that the mineralizing fluids were brines derived from the basin (e.g., Alexandre et al., 2005; Cuney et al., 2003; Derome et al., 2005; Kyser et al., 2000; Mercadier et al., 2012; Richard et al., 2011), but the driving forces for the basinal fluids to migrate to the unconformity between the basin and the basement, where uranium mineralization took place, are still not well understood (Chi et al., 2011). Various fluid-flow models have been proposed or implied for the Athabasca basin in previous studies, including large-scale convection related to effects of the thermal gradient (Boiron et al., 2010; Hoeve and Sibbald, 1978; Raffensperger and Garven, 1995) and deposit-scale convection related to heat anomalies associated with the high heat conductivity of graphite (Hoeve and Quirt, 1984), gravity-driven flow (Alexandre and Kyser, 2012; Derome et al., 2005), compaction-driven flow (Hiatt and Kyser, 2007), and deformation-induced fluid flow (Cui et al., 2012). In order to evaluate these potential fluid flow models, and eventually use them to predict favorable sites of mineralization based on the reverse engineering approach (e.g., L. Zhang et al., 2011; Y. Zhang et al., 2011; Zhao et al., 2012a), it is important to know the background fluid pressure and temperature of the basin, as they provide constraints on initial and boundary

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conditions. A previous study has shown that fluid overpressure caused by sediment compaction was small in the Athabasca basin, and that the fluid pressure within the basin was near the hydrostatic regime throughout the sedimentation history (Chi et al., 2013). It was also shown that the thermal profile of the basin was not disturbed by the slow fluid flow related to sediment compaction (Chi et al., 2013).

Although the Athabasca basin is generally characterized by reddish lithologies, which are poor in organic matter, the upper part of the preserved basin stratigraphy, particularly the Douglas Formation, is known to contain significant amounts of organic matter, with total organic carbon (TOC) up to 3.56 wt.% (Stasiuk et al., 2001). An average vitrinite reflectance equivalent value of 1.4% Ro in the Douglas Formation suggests a maximum burial temperature of 160° to 200 °C, which corresponds to the late oil to early dry gas zone of thermal maturity (Stasiuk et al., 2001). Furthermore, oil inclusions have been identified in the shales and siltstones of the Douglas Formation as well as in sandstones in the underlying formations (Stasiuk et al., 2001). It is widely accepted that the generation of oil and gas, with accompanying volume increase due to transformation of organic matter from solid to liquid or gas, is one of the most important mechanisms causing fluid overpressure, next to sediment compaction (Swarbrick et al., 2002), as demonstrated for example by numerical modeling for the Paleozoic Anticosti basin in eastern Canada (Chi et al., 2010) and the Paleozoic–Mesozoic Ordos basin in northern China (Xue et al., 2011). In the case of the Athabasca basin, however, it remains to be determined how the generation of hydrocarbons in the Douglas Formation may have affected the fluid pressure regime and fluid flow pattern in the basin.

Hydrocarbons have been documented in many of the uranium deposits in the Athabasca basin, and their origins and roles in uranium mineralization have been debated for a long time (e.g., Annesley et al., 2001; Hoeve and Sibbald, 1978; Kyser et al., 1989; Landis et al., 1993; Leventhal et al., 1987; McCready et al., 1999; Stasiuk et al., 2001; Wilson et al., 2007). In the original unconformity-type uranium mineralization model, Hoeve and Sibbald (1978) suggested that mineralization took place when a uranium-bearing, oxidizing fluid from the basin mixed with a reduced fluid from the basement near the unconformity, with the reductant (methane) being derived from nearby graphite-rich zones in the basement. Leventhal et al. (1987) and Kyser et al. (1989) argued that the bitumen found in the ores was not derived from graphite based on the carbon isotope compositions of the bitumen and graphite, and Leventhal et al. (1987) suggested that the hydrocarbons were emplaced after uranium mineralization. Wilson et al. (2007) provided biomarker evidence to indicate that at least part of the bitumen in the ores was sourced from the Douglas Formation, and also suggested that the bitumen postdates the ores and did not play any role in mineralization. Putting aside the controversy about the relative timing of bitumen and mineralization, it is of interest for this paper to examine whether or not the hydrocarbons generated in the Douglas Formation could have migrated to the basal part of the basin and the top of the basement.

Numerical modeling has been widely used to simulate fluid flow and chemical reaction processes in various geological environments including mineralization systems (e.g., Appold and Garven, 2000; Bethke and Marshak, 1990; Cathles, 1981; Chi and Savard, 1998; Chi and Xue, 2011; Chi et al., 2006, 2011, 2013; Garven, 1985, 1995; Gow et al., 2002; Hobbs et al., 2000; Ingebritsen, and Appold, 2012; Ju et al., 2011; Lin et al., 2003, 2006, 2008, 2009; Liu et al., 2005, 2008; Norton, 1978; Oliver et al., 2006; Ord et al., 2002; Schaubs and Zhao, 2002; Schmidt Mumm et al., 2010; Sorjonen-Ward et al., 2002; Xing et al., 2008; Xue et al., 2010, 2011; Zhang et al., 2003, 2008; L. Zhang et al., 2011; Y. Zhang et al., 2011; Zhao et al., 2008a) and geoenvironmental systems (e.g., Awadh et al., 2013; Charifo et al., 2013; Khalil et al., 2013; Mugler et al., 2012; Sung et al., 2012; Zhao et al., 2010, 2011, 2012b). The simulated numerical models have varied from generic models (e.g., Zhao et al., 1997, 2004, 2007) to realistic geological conceptual models (e.g., Liu et al., 2010, 2011; Zhao et al., 2008b). In terms of simulating chemical reaction processes, the simulated system can involve either single chemical reaction (e.g., Zhao et al., 2008c, 2008d,) or multiple complicated chemical reactions that take place in real rocks (e.g., Alt-Epping and Zhao, 2010). Numerical modeling was also used to simulate fluid flow, heat transfer and hydrocarbon transport in sedimentary basins (e.g., Chi et al., 2010; Garven, 1989; Zhao et al., 1999). As a result of this wide range of applications, numerical modeling has now become an indispensable method for dealing with a broad range of geoscience and geoenvironmental problems (Zhao et al., 2009).

In this paper, numerical modeling was carried out to examine the effect of hydrocarbon generation in the Douglas Formation on fluid pressure and fluid flow patterns in the Athabasca basin, built on a previous numerical modeling of fluid pressure related to sediment compaction in the same basin (Chi et al., 2013). The potential for hydrocarbons to migrate from the Douglas Formation to stratigraphically lower successions and the basement is evaluated, and the implications for uranium mineralization are also discussed.

2. Geological setting

The Athabasca basin is a Paleoproterozoic to Mesoproterozoic basin of mainly siliciclastic rocks resting unconformably on Archean to Paleoproterozoic basement (Card et al., 2007; Jefferson et al., 2007; Ramaekers et al., 2007). The western part of the basin is underlain by basement rocks belonging to the Taltson magmatic zone and the Rae Province, and the eastern part by the Hearne Province, which is bounded in the east by the Trans-Hudson orogen (Fig. 1a). Both the Rae and Hearne provinces are divided into different domains, of which the Mudjatik and Wollaston domains underlie the eastern part of the Athabasca basin, where the most important uranium deposits are situated (Fig. 1a). The basement rocks consist of Archean granitoid gneiss and metasedimentary rocks (mainly in Rae) and metavolcanic rocks (mainly in Hearne), overlain by Paleoproterozoic metasedimentary rocks, which are divided into the Murmac Bay, Thluicho Lake and Martin groups in Rae, and the Hurwitz Group and partly coeval Wollaston Supergroup in Hearne (Card et al., 2007).

The flat-lying, unmetamorphosed sedimentary rocks in the Athabasca basin belong to the Athabasca Group, which is divided into the following formations (from oldest to youngest): Fair Point, Read, Smart (may be a distal facies equivalent to Read), Manitou Falls, Lazenby Lake, Wolverine Point, Locker Lake, Otherside, Douglas, and Carswell (Fig. 1b; Ramaekers et al., 2007). Most of these formations are composed of sandstone with less than 5% of shale, except for the Wolverine Point Formation which comprises quartz arenite with abundant mudstone in the lower part, the Douglas Formation consisting mainly of mudstone and siltstone, and the Carswell Formation comprising mainly carbonates. The Douglas Formation is characterized by thin-laminated, black, carbonaceous mudstone and siltstone, with TOC ranging from < 0.25 to 3.56 wt.% (Stasiuk et al., 2001), and an average TOC of 0.74 wt.%. Detailed subdivisions of the formations and their lithologies are described by Ramaekers et al. (2007) and summarized in Chi et al. (2013).

It has been estimated that more than 5 km of strata may have been eroded above the youngest preserved rocks in the basin, based on fluid inclusion data from the Carswell structure and the Rumpel Lake drill core in the central part of the basin, which suggest a paleogeothermal gradient of 35 °C/km (Pagel, 1975). A similar estimate is also derived from the maximum burial temperatures of 160° to 200 °C for the Douglas Formation based on organic matter maturation (Stasiuk et al., 2001), assuming a thermal gradient of 35 °C/km. However, the lithologies of the eroded strata are unknown. The age and duration of sedimentation in the basin has been loosely constrained to be from 1760 Ma to 1500 Ma (Ramaekers et al., 2007), based on estimation of a ca. 1750 Ma age for onset of rapid erosion of the Trans-Hudson orogen (Alexandre et al., 2009; Annesley et al., 1997; Kyser et al., 2000; Orrell et al., 1999), a U–Pb age of 1644 ± 13 Ma for igneous zircon in a tuffaceous unit in the Wolverine Point Formation (Rainbird et al., 2007),