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Numerical modeling of fluid pressure regime in the Athabasca basin and implications for fluid flow models related to the unconformity-type uranium mineralization

Guoxiang Chi [a],*, Sean Bosman [b], Colin Card [b]

[a] Department of Geology, University of Regina, 3737 Wascana Parkway, Regina, SK, Canada S4S 0A2
[b] Saskatchewan Geological Survey, 200-2101 Scarth Street, Regina, SK, Canada S4P 2H9

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ABSTRACT

Various fluid-flow models have been suggested for the formation of unconformity-type uranium deposits in the Athabasca basin, including fluid flow driven by fluid overpressure, topographic relief, fluid density variation due to temperature or salinity change, and tectonic deformation. In order to evaluate the fluid-flow mechanisms responsible for mineralization, it is necessary to know the distribution and evolution of fluid pressure during the history of the basin. A numerical modeling study of the development of fluid overpressure due to disequilibrium sediment compaction was carried out, and the results suggest that no significant fluid overpressure was developed in the basin throughout the sedimentation history. 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 show a thermal anomaly. The development of near-hydrostatic pressure regime in the Athabasca basin may have facilitated circulation of oxidizing fluids from the shallow part of the basin into the basal part, favoring the formation of unconformity-type uranium deposits, as opposed to other sedimentary basins where elevated fluid overpressures within the lower part of the basin may have prevented downward infiltration of oxidizing fluids, limiting uranium mineralization to the upper part of the basin.

1. Introduction

The Athabasca basin in northern Saskatchewan and Alberta hosts the world's largest high-grade uranium deposits, which are generally located near the unconformity between late Paleoproterozoic to Mesoproterozoic sedimentary rocks of the Athabasca Group and Archean to Paleoproterozoic metamorphic rocks in the basement (Jefferson et al., 2007; Kyser and Cuney, 2008). 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), although it is uncertain whether uranium was derived from the basin (Fayek and Kyser, 1997; Hoeve et al., 1980; Kotzer and Kyser, 1995; Kyser et al., 2000) or from the basement (Cuney et al., 2003; Dahlkamp, 1978; Hetch and Cuney, 2000; Richard et al., 2010). Various fluid-flow models related to uranium mineralization have been proposed or implied in previous studies (Chi et al., 2011), including large-scale convection related to thermal gradient (Boiron et al., 2010; Hoeve and Sibbald, 1978; Raffensperger and Garven, 1995) and deposit-scale convection related to heat anomaly associated with 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). Some of these models assume that the fluid pressure in the basin was initially near hydrostatic (Cui et al., 2012; Raffensperger and Garven, 1995), some implied significant overpressure (Derome et al., 2005; Hiatt and Kyser, 2007), and some predict that the fluid pressure at the site of mineralization may have fluctuated between underhydrostatic and near-lithostatic, either under a constant subhorizontal compressional stress regime (Tourigny et al., 2007), or in response to alternating compressional and extensional stress regimes (Cui et al., 2012). Therefore, the fluid pressure regime (hydrostatic, lithostatic, or intermediate) in the Athabasca basin during the history of sedimentation (1750 to <1541 Ma; Jefferson et al., 2007) remains unknown, which significantly hinders our understanding of the fluid-flow mechanisms responsible for uranium mineralization, as the time of primary uranium mineralization (mainly from ca. 1600 to 1500 Ma; Alexandre et al., 2009; Jefferson et al., 2007; Kyser and Cuney, 2008) largely overlaps with sedimentation in the basin. This paper addresses this problem through numerical modeling of the development of fluid overpressure (the difference between fluid pressures and hydrostatic values; Bethke, 1985) throughout the depositional history of the basin, using the software Basin2 (Bethke et al., 1993). We choose to use Basin2 because it is best suited for addressing the problem of disequilibrium sediment compaction (i.e., sediment compaction is hindered because pore fluid cannot escape rapidly enough due to low-permeability), which is the main cause of fluid overpressure in sedimentary basins (Swarbrick

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* Corresponding author.
E-mail address: guoxiang.chi@uregina.ca (G. Chi).

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et al., 2002), and it can readily model the evolution of the basin with time. Numerical modeling of fluid flow has become increasingly important in understanding mineralization processes (Zhao et al., 2012), and various numerical models have been investigated for a given mineralization system, including unconformity-type uranium mineralization (Cui et al., 2012; Oliver et al., 2006; Raffensperger and Garven, 1995). However, it should be noted that the focus of this paper is on the fluid pressure regime during sedimentation, not on modeling the process of uranium mineralization. Nevertheless, the results of the present study have important implications for fluid flow models related to uranium mineralization, which are discussed in this paper.

2. Geological background

The Athabasca basin is composed of flat-lying Paleoproterozoic to Mesoproterozoic sedimentary rocks of the Athabasca Group, underlain by strongly deformed Archean to Paleoproterozoic metamorphic rocks in the basement (Jefferson et al., 2007). The unconformity between the basin and basement is marked by a paleo-weathering profile of variable thicknesses developed at the top of the basement (Jefferson et al., 2007). Typically, uranium mineralization occurs in basement rocks immediately below and in sandstones immediately above the unconformity, although mineralization 10s to 100 s of meters below the unconformity has been discovered.

2.1. Basement rocks

The basement rocks belong to, from west to east, the Taltson magmatic zone, the Rae Province, and the Hearne Province, the latter two forming the Churchill Province and being separated by the Snowbird tectonic zone (Fig. 1; Card et al., 2007). The Taltson magmatic zone, considered to be the southern extension of the Thelon tectonic zone, which separates the Rae Province from the Slave Province to the west (Hoffman, 1988), is composed of a variety of 1.99–1.92 Ga plutonic rocks intruding 3.2–2.14 Ga metamorphic complexes of amphibolite to granitic gneiss (Card et al., 2007). In Saskatchewan, the Rae Province is divided into several domains including Beaverlodge, Zemlak, Tantato, Lloyd, and Clearwater, whereas the Hearne Province comprises the Virgin River, Mudjatik, Wollaston and Peter Lake domains, which are bounded by the Trans-Hudson Orogen to the east (Fig. 1; Card et al., 2007). Both the Rae and Hearne provinces in Saskatchewan contain ca. 3.0 Ga granitoid gneiss and >2.6 Ga metasedimentary rocks (mainly in Rae) and metavolcanic rocks (mainly in Hearne), followed 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). Paleoproterozoic metasedimentary rocks contain graphitic metapelitic units, mainly in the lower part of the Wollaston Supergroup in the Hearne Province, and in the Rae Province. Paleoproterozoic granitic intrusions with ages similar to those in the Taltson–Thelon and Trans-Hudson orogens are common in the Rae and Hearne provinces, respectively.

2.2. Sedimentary rocks in the Athabasca basin

The non-metamorphosed 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. 1; Ramaekers et al., 2007). The Fair Point Formation is mainly composed of conglomerate and conglomeratic quartz arenite, with minor pebbly mudstone. The Read Formation consists of conglomerate and quartz arenite, with minor pebbly mudstone, and the Smart Formation of quartz arenite, with local pebbly mudstone. The Manitou Formation is composed of, from lower to upper, pebbly quartz arenite with >2% conglomerate in the Bird Member (MFb), pebbly and non-pebbly quartz arenite with >1% clay intraclasts in the Raibl Member (MFr), non-pebbly and pebbly quartz arenite with >1% clay intraclasts in the Warnes Member (MFw) (note: MFr and MFw are considered laterally equivalent to MFb), quartz arenite and pebbly quartz arenite in the Collins Member (MFc), and quartz arenite with >1% clay intraclasts in the Dunlop Member (MFd). The Lazenby Lake Formation consists mainly of quartz arenite, with siltstone and mudstone, and local conglomerate, and the Wolverine Point Formation comprises quartz arenite with abundant mudstone in the lower part. The Locker Lake Formation is composed of conglomeratic quartz arenite, and the Otherside Formation of quartz arenite and pebbly quartz arenite. The Douglas Formation consists of mudstone and fine to very fine quartz arenite, while the Carswell Formation comprises carbonates including stromatolitic to massive dolomite, stromatolite, and oolite with siliciclastic interbeds (Ramaekers et al., 2007). The Carswell Formation was formed in marginal marine environments, the Douglas Formation in playa lakes or lagoons, and the rest of the Athabasca Group were deposited in braided river systems (Ramaekers et al., 2007).

The lithostratigraphic units are grouped into 4 sequences separated by major unconformities: sequence 1 comprising the Fair Point Formation, sequence 2 of Read/Smart and Manitou Falls formations, sequence 3 of Lazenby Lake and Wolverine Point formations, and sequence 4 from Locker Lake to Carswell formations (Ramaekers et al., 2007). Based on the isopachs of the 4 sequences, the Athabasca basin is divided into 3 subbasins: the Jackfish subbasin in the west, where the Fair Point Formation (sequence 1) was deposited; the Cree subbasin in the east, where sequence 2 is thickest; and the Mirror subbasin in the mid-west, where sequences 2 and 3 are thickest (Figs. 1 and 2; Ramaekers et al., 2007). Sequence 1 is only exposed locally in the west margin of the basin, sequence 2 mainly in the east, and sequences 3 and 4 in the western part of the basin (Figs. 1 and 2; Ramaekers et al., 2007). The Douglas and Carswell formations only occur around the Carswell impact structure (Fig. 1; Ramaekers et al., 2007). Despite the overall west–east orientation of the Athabasca basin (Fig. 1), a number of "troughs" developed during the deposition history of the basin are oriented southwest–northeast, which is similar to the framework structures in the basement, suggesting multiple reactivations of the basement faults during the sedimentation in the basin (Jefferson et al., 2007). Provenance and sedimentary structure studies indicate that the sediments were derived from the east and south most of the time, except during the deposition of sequence 3, when the provenance was mainly from the south (Ramaekers et al., 2007).

The sedimentation in the Athabasca basin is inferred to have started after ca. 1750 Ma, based on a U–Pb titanite age of ca. 1752 Ma in the Wollaston domain (Annesley et al., 1997), ^{207}P/^{206}Pb and U–Pb rutile ages around 1750 Ma in the Mudjatik domain (Orrell et al., 1999), and the rapid erosion of the Trans-Hudson Orogen at ca. 1750 as indicated by Ar–Ar ages (Alexandre et al., 2009; Kyser et al., 2000). This age may represent the maximum age of the Fair Point Formation, while a younger age of 1740–1730 Ma has been suggested for the Manitou Falls Formation (Alexandre et al., 2009; Rainbird et al., 2006). An age of 1644 ± 13 Ma was reported for igneous zircon in tuffaceous units in the Wolverine Point Formation (Rainbird et al., 2007), and a Re–Os isochron age of 1541 ± 13 Ma was obtained for carbonaceous shales in the Douglas Formation (Creaser and Stasiuk, 2007). Microthermometric studies of fluid inclusions in authigenic quartz in sandstones from the Carswell structure and the Rumpel Lake drill core in the central part of the Cree subbasin suggest a paleogeothermal gradient of 35 °C/km and that more than 5 km of strata may have been eroded above the youngest preserved rocks in the basin (Pagel, 1975). The ages of these eroded strata are unknown, but they are likely older than the 1270 Ma mafic dikes (LeCheminant and Heaman, 1989) that cut the Athabasca Group and basement rocks. Also unknown are the ages and duration of the hiatuses between the different sequences.