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Thermal profiles inferred from fluid inclusion and illite geothermometry from sandstones of the Athabasca basin: Implications for fluid flow and unconformity-related uranium mineralization

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ABSTRACT

The Proterozoic Athabasca basin and underlying basement host numerous unconformity-related uranium deposits that were formed from extensive fluid circulation near the basement-cover interface. Although it is generally agreed that the mineralizing fluids were basinal brines, it is still unclear what driving forces were responsible for the circulation of the basinal fluids. Because different fluid flow driving forces are associated with different thermal profiles, knowing the basin-scale distribution of paleo-fluid temperatures can help constrain the fluid flow mechanism. This study uses fluid inclusions entrapped in quartz overgrowths and authigenic illite in sandstones from three drill cores (WC-79-1, BL-08-01, and DV10-001) in the central part of the Athabasca basin as thermal indicators of paleo-fluids in the basin. A total of 342 fluid inclusions in quartz overgrowths were studied for microthermometry. The homogenization temperatures (T_h) range from 50° to 235 °C, recording the minimum temperatures in various diagenetic stages. Temperatures estimated from illite geothermometry (121 points) range from 212° to 298 °C, which are systematically higher than (partly overlapping) the T_h values, suggesting that illite was precipitated in hotter fluids following the formation of quartz overgrowths. Neither the fluid inclusion T_h values nor the illite temperatures show systematic increase with depth in individual drill cores. This, together with the high illite temperatures that cannot be explained by burial at a normal geothermal gradient (35 °C/km), is interpreted to indicate that basin-scale fluid convection took place during the diagenetic history of the basin. Prolonged fluid convection is inferred to be responsible for delivering uranium (extracted from the basin or the upper part of the basement) to the unconformity, where uranium mineralization took place due to redox reactions associated with fluid-rock interaction or structurally controlled fluid mixing.

1. Introduction

Basin-scale fluid flow in sedimentary basins played a significant role in the formation of many mineral and petroleum deposits (Bethke and Marshak, 1990; Garven and Raffensperger, 1997; Cathles and Adams, 2005). The mechanism of such fluid flow, for example that responsible for the formation of Mississippi Valley-type (MVT) Zn–Pb deposits, has been a subject of scientific debates for over three decades, one of the focuses being whether or not a given fluid flow model can explain the heat anomaly observed in the deposits (Cathles and Smith, 1983; Anderson and Macqueen, 1988; Bethke and Marshak, 1990; Garven et al., 1993; Garven and Raffensperger, 1997; Cathles and Adams, 2005). This is understandable because fluid flow is always associated with heat transport, and different fluid flow mechanisms may result in different thermal profiles (Duddy et al., 1994; Deming, 1994; Jessop and Majorowicz, 1994; Phillips, 2009; Ingebritsen and Appold, 2012; Chi, 2015). Thus, the study of thermal profiles in sedimentary basins is important for constraining fluid flow models. Fluid flow mechanisms related to the formation of sedimentary basin-hosted (especially unconformity-related) uranium deposits have also been extensively studied (Sanford, 1992; Raffensperger and Garven, 1995a, b; Chi et al., 2011, 2013, 2014; Cui et al., 2010, 2012a, b; Chi and Xue, 2014), but so far little attention has been paid to the thermal effects of the fluid flow as was done for the MVT deposits.

The unconformity-related uranium (URU) deposits, which are best developed in Proterozoic basins in northern Canada and northern Australia, especially the Athabasca basin in northern Saskatchewan (Canada; Fig. 1a), represent the richest uranium deposits in the world (Jefferson et al., 2007; Fayek, 2013). The formation of these deposits has been related to circulation of large amounts of basinal fluids, facilitated by high permeabilities due to dominance of sandstones in the basins (Hoeve and Sibbald, 1978; Hoeve and Quirt, 1984; Wilson and Kyser, 1987; Kotzer and Kyser, 1990; Hiatt and Kyser, 2000; Cuney et al., 2003; Kyser et al., 2000; Richard et al., 2011, 2014; Mercadier et al., 2012). However, the driving forces controlling fluid flow are still controversial. Large-scale convection related to a normal geothermal gradient was proposed by Hoeve and Sibbald (1978) and Boiron et al.

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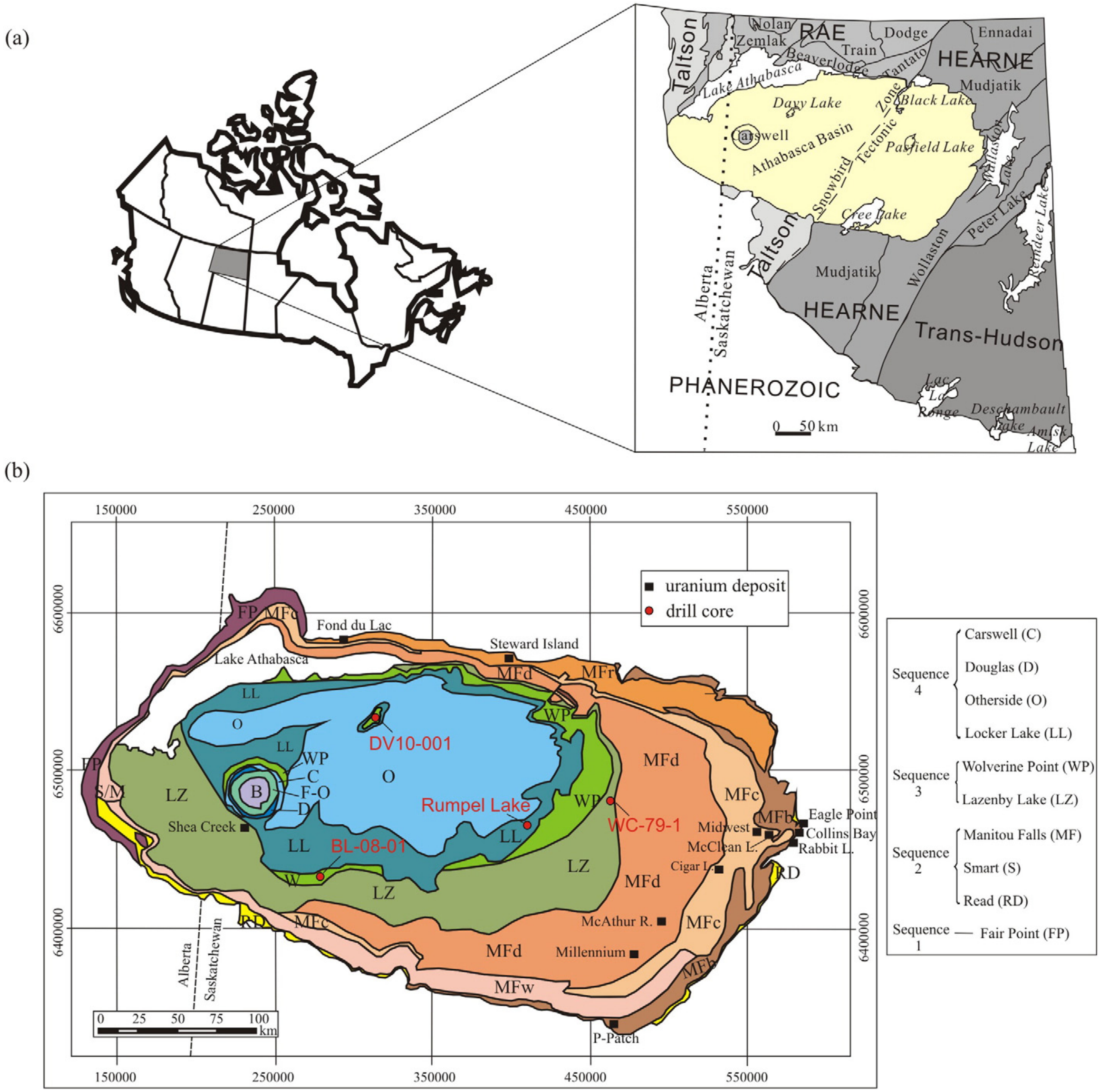

Fig. 1. (a) Location of the Athabasca basin in the regional tectonic framework (after Card, 2012). (b) Regional geological map of the Athabasca basin showing each formation, major uranium deposits, and the location of drill holes WC-79-1, BL-08-01, DV10-001, and Rumpel Lake (modified from Ramaekers et al., 2007, Jefferson et al., 2007; Bosman et al., 2011, 2012). B — basement; FP — Fair Point; S/M — undifferentiated Smart and/or Manitou Falls; RD — Read; MF — Manitou Falls (b — Bird; r — Raibl; w — Warnes; c — Collins; d — Dunlop); LZ — Lazenby Lake; W — Wolverine Point; LL — Locker Lake; O — Otherside; D — Douglas; C — Carswell; F–O — undivided Fair Point to Otherside formations. Note the UTM coordinate is used.

(2010) as the main mechanism responsible for fluid flow related to URU mineralization in the Athabasca basin, and was shown to be plausible using numerical modeling (Raffensperger and Garven, 1995a, b; Cui et al., 2010, 2012a, b). Topography-driven fluid flow was implied in some schematic models (Derome et al., 2005; Hiatt and Kyser, 2007; Boiron et al., 2010) and proposed to be responsible for URU mineralization in the Athabasca basin (Alexandre and Kyser, 2012). Both thermal convection and topography-driven flow are consistent with the near-hydrostatic fluid pressure regime in the Athabasca basin, as demonstrated by numerical modeling (Chi et al., 2013, 2014). Compaction-driven fluid flow was implied in hydrostratigraphic studies of sandstones of the Athabasca basin (Hiatt and Kyser, 2007), but it has been shown that such fluid flow was too slow to result in any significant thermal disturbance in the basin (Chi et al., 2013, 2014). Furthermore, based on the observation that most unconformity-related uranium deposits are spatially associated with faults crosscutting the unconformity, it was demonstrated that fluid flow related to uranium mineralization may be related to deformation along fault zones (Cui et al., 2012a), and mixed or alternative convection and deformation-driven fluid flow models have been advocated (Hoeve and Quirt, 1984, 1987; Raffensperger and Garven, 1995b; Cui et al., 2012a; Li et al., 2015). The uncertainties on fluid flow models related to URU mineralization are in part related to the poor understanding of thermal profiles related to fluid flow either at the basin scale or the deposit scale.