Journal of Geochemical Exploration 144 (2014) 12–27

Contents lists available at ScienceDirect

Journal of Geochemical Exploration

journal homepage: www.elsevier.com/locate/jgeoexp

Effect of graphite zone in the formation of unconformity-related uranium deposits: Insights from reactive mass transport modeling

Yousef Beiraghdar Aghbelagh [a], Jianwen Yang [a,b,*]

[a] Department of Earth and Environmental Sciences, University of Windsor, Windsor, Ontario N9B 3P4, Canada
[b] College of Earth Sciences, Guilin University of Technology, Guilin, Guangxi 541004, China

ARTICLE INFO

Article history:
Received 24 September 2013
Accepted 26 January 2014
Available online 4 February 2014

Keywords:
Unconformity-related uranium
Reactive mass transport modeling
Oxygen fugacity
Graphite zone
Computational modeling

ABSTRACT

In this study, reactive mass transport modeling is conducted for evaluating the role of faulted graphite zones in the formation of unconformity-related uranium (URU) deposits. For this aim, two different reducing mechanisms are examined for the precipitation of uraninite in a typical URU deposit. In the first mechanism, precipitation of the uraninite involves methane as a reducing agent which is produced by the alteration of the graphite zone. The second reducing mechanism does not incorporate methane as a reducing agent, and oxygen is used for formulating the redox reaction of uraninite precipitation. Numerical simulations show the following results. Firstly, by employing either reducing mechanisms, uraninite can precipitate in the basement close to the unconformity interface. Secondly, uraninite can precipitate below the unconformity interface away from the faulted graphite zone even if methane is not involved as a reducing agent. Physiochemical parameters such as oxygen fugacity and temperature play a significant role in localization of uraninite. Localization of uraninite below the unconformity interface is related to the decrease of oxygen fugacity, generally resulting from the interaction of oxidized uranium-bearing fluids with reductants. Through the second reducing mechanism, uraninite cannot precipitate around the faulted graphite zone. In comparison with the precipitation by the first reducing mechanism, it takes longer time for uraninite to precipitate through the second mechanism, and the volume fraction of uraninite precipitated by the second mechanism is lower than that by the first mechanism. Finally, faulted graphite zone has a major role in providing the pathway for transporting the fluid. The uranium bearing brines flow into the faulted graphite zone and interact with the basement lithology. Also, the basal fluids use faulted graphite zone as a conduit to mix with the basinal fluids. Maximum fluid flow rate happens along the faulted graphite zone because of the high permeability of this zone in comparison with that of other stratigraphic units present in the model.

1. Introduction

Unconformity-related uranium (URU) deposits are the most important and profitable deposits among other types of uranium deposits (De Veslud et al., 2009; Derome et al., 2005). They are located within or around basal unconformities between Proterozoic basin fill and the underlying Archean granitoid gneisses and Paleoproterozoic metamorphic rocks, where reductants and faults exist (Cui et al., 2012; Jefferson et al., 2007). The Athabasca Basin, a premier host of URU deposits, is located in the northern part of Saskatchewan and Alberta. It occurs as a series of northeast–southwest-oriented subbasins controlled by major Hudsonian faults rooted in the basement rocks (Hoeve and Quirt, 1984; Hoeve and Sibbald, 1978; Kotzer and Kyser, 1995; Ramaekers, 1990). These faults were reactivated after the filling of the Athabasca Basin (Hoeve and Sibbald, 1978; Kotzer and Kyser, 1995) and have remained active until recent times (Hoeve and Quirt, 1984). Most of the known URU deposits in the Athabasca Basin are located in the eastern part of the basin, particularly in the vicinity of the graphite-rich Cable Bay shear zone that occurs between the Mudjatik and the Wollaston domains (Derome et al., 2005). McArthur River deposit is a good example for the URU deposits located in the eastern part of the Athabasca Basin. The deposit is structurally controlled by the northeast-trending, southeast dipping, graphite-rich reverse fault which is rooted in the basement and extended several meters over the unconformity surface into the basin (Derome et al., 2005). The existence of URU deposits is not limited to the eastern part of the Athabasca Basin and there are some URU deposits in other parts of the basin as well. The Shea Creek area, for example, is located in the western part of the Basin. In this area, three main Paleoproterozoic basement lithostratigraphic units have been identified: a metasedimentary unit (consisting of metapelites and garnetites) in which graphite is mainly concentrated along reverse faults, surrounded by two metaigneous

---

* Corresponding author at: Department of Earth and Environmental Sciences, University of Windsor, Windsor, Ontario N9B 3P4, Canada. Tel.: +1 519 253 3000x2181.
E-mail address: jianweny@uwindsor.ca (J. Yang).

0375-6742/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.gexplo.2014.01.020

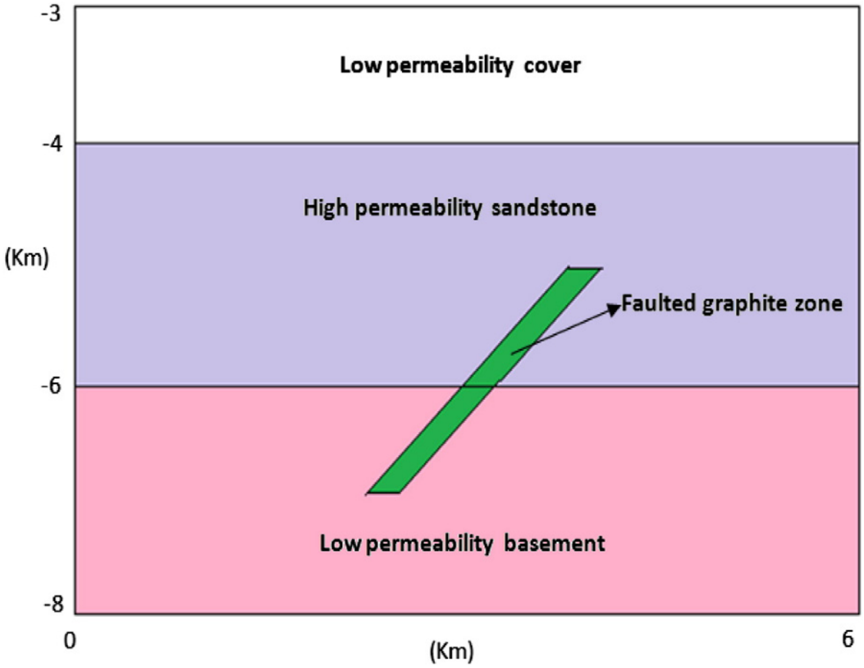

Fig. 1. Conceptual model used in the simulation of URU deposits.
After Cui et al. (2012).

felsic gneiss units, one above and another below the metasedimentary package (De Veslud et al., 2009). Despite the general understanding that graphite-rich shear zones in the Athabasca Basin have a critical role in providing the reducing agents (Hoeve and Sibbald, 1978), enhancing the local permeability, and focusing fluid flow (Kotzer and Kyser, 1990; Kyser et al., 1989; Raffensperger, 1993; Raffensperger and Garven, 1995a,b), its exact role in the formation of these deposits is still not fully understood. Some uranium deposits can form in the absence of graphitic units (e.g., Kiggavik, Fuchs and Hilger, 1989; and some of the deposits at Cluff Lake, Jefferson et al., 2007), but they are in the minority. It is still unsure whether super high-grade deposits, such as the McArthur River, can form without the presence of graphite zone (Jefferson et al., 2007).

Computational simulation in the computational geoscience field (Zhao et al., 2008a, 2009 and the references therein included) has provided an important, if not unique, way for simulating geological phenomena that take place within the crust of the Earth. Owing to the robust and practical nature, it has been extensively used to deal with fluid flow processes associated with not only a wide range of ore-forming problems (Gow et al., 2002; Hobbs et al., 2000; Ord et al., 2002; Sorjonen-Ward and Zhang, 2002; Zhang et al., 2003, 2008), but also various types of geoscience problems (Awadh et al., 2013; Lin et al., 2003, 2006, 2008, 2009; Liu and Zhao, 2010; Liu et al., 2005, 2008, 2011; Mugler et al., 2012; Schmidt Mumm et al., 2010; Xing and Makinouchi, 2008; Yan et al., 2003; Zhang et al., 2011; Zhao, 2009; Zhao et al., 2008b, 2010). The produced simulation results have greatly enhanced our understanding of controlling dynamic mechanisms behind the mineralization within the upper crust of the Earth (Gow et al., 2002; Ord et al., 2002; Sorjonen-Ward and Zhang, 2002). Furthermore, computational simulation has also been used to solve groundwater pollution problems in the geoevironmental field (Charifo et al., 2013; Khalil et al., 2013; Sung et al., 2012; Zhao et al., 2008b, 2010).

In this study, reactive mass transport modeling is conducted for evaluating the role of faulted graphite zone in the formation of URU deposits, which couples the processes of fluid flow, heat transfer, solute transport, and geochemical reactions in a collective manner. Reactive mass transport modeling has been applied successfully to the study of a number of different types of ore deposits, including URU deposits (Raffensperger and Garven, 1995b), copper (He et al., 1999; Kuhn et al., 2004; Lichtner and Biino, 1992a), bauxite (Soler and Lasaga, 1998), and Mississippi Valley-type (Appold and Garven, 2000; Lichtner and Biino, 1992b). A previous study by Raffensperger and Garven (1995b) predicted the formation of uranium ore deposits in the Athabasca Basin, inside the sandstone cover, over a time scale of 0.1 to 1 Ma. In their conceptual model the graphite unit was only limited to the basement. However, it is now clear that these faulted graphite units (e.g., McArthur River deposit, Derome et al., 2005) are rooted in

Table 1
Major physical properties of various hydrostratigraphic units.
Based on previous study on URU deposits by Raffensperger and Garven (1995b) and Cui et al. (2012).

Property	Confining unit	Sandstone unit	Basement unit	Faulted graphite zone
Density (kg/m^3)	2400	2500	2650	2400
Porosity	0.15	0.2	0.1	0.2
Permeability (m^2)	1×10^{-15}	3×10^{-13}	3×10^{-16}	1×10^{-12}
Heat conductivity (W/m·°C)	2.5	3.5	2.5	4
Specific heat capacity (J/kg·°C)	803	803	803	803
Pore fluid compressibility (1/Pa)	3.5714×10^{-11}	3.125×10^{-11}	2.0202×10^{-11}	4.2918×10^{-11}
Pore fluid expansivity (1/°C)	8.0×10^{-6}	1.0×10^{-5}	8.0×10^{-6}	1.0×10^{-5}