AAPG Search and Discovery Article #90172 © CSPG/CSEG/CWLS GeoConvention 2010, Calgary, Alberta, Canada, May 10-14, 2010

Formation of unconformity-related uranium deposits: perspectives from numerical modeling

Tao Cui*, Jianwen Yang, Iain M. Samson
Department of Earth and Environmental Sciences, University of Windsor, Windsor, Ontario, Canada, N9B 3P4
taocuisunny@gmail.com

Summary

A series of theories have been proposed to explain the formation of unconformity-related uranium deposits. However, ore-forming fluid flow mechanisms responsible for uranium mineral precipitation are still not completely understood. In this study, a simplified conceptual model is constructed by integrating some common features of typical deposits of this type in the Athabasca, Thelon and Kombolgie basins. Based on the model, a series of numerical scenarios are designed to examine the roles of various factors in controlling ore-forming fluid flow. Our modeling suggests that thermal-driven free convection may develop throughout the thick sandstone sequence at a geothermal gradient range of 25-35 °C during tectonically quiet periods, with a maximum velocity ca.1 m/yr. However, reactivation of basement faults resulting from far-field tectonic processes suppresses free convection and leads to deformation-dominated fluid flow systems. For compressive tectonic settings, reduced basement fluids flow upwards along fracture zones and would mix with uranium-bearing fluids in the sandstone sequence. In extensional settings, oxidized uraniferous fluids in the sandstone sequence flow down the faults into the basement, where they may encounter reduced minerals or fluids. Maximum flow rates may reach 40 m/yr in fracture zones during fault reactivation, for strain rates ranging from 10^{-14} to 10^{-12} s^{-1}.

Introduction

Unconformity-related uranium deposits, mainly hosted in Paleoproterozoic basins in Canada and Australia, currently supply 30% of global uranium (Kyser and Cuney, 2009). However, genetic models for these deposits remain controversial. Thermally driven convection has been proposed to be responsible for the leaching of uranium from sandstone cover sequences (Raffensperger and Garven, 1995; Cui et al., 2010). However, convection is insufficient to explain the interaction between the oxidized basinal fluids and the reduced basement fluids or graphite, and the close spatial association with faults, without considering tectonic deformation.

It has been proposed that tectonic deformation can be responsible for the migration of ore-forming fluids (e.g., Cox, 2005; Hobbs, 2004; Sibson, 2001). In particular, Oliver et al. (2006), using numerical modeling, have suggested that extension may cause fluid flow across basement-cover interfaces during basin-related mineralization. This study aims to investigate tectonically and thermally driven fluid flow and its influence on the formation of unconformity-related uranium deposits. First, a simplified hydrogeological model was constructed by integrating existing geology, geophysical and geochemical data for the Athabasca, Thelon and Kombolgie basins. A series of numerical experiments were then carried out to study the relationship between tectonic deformation, thermal structure, mineralizing fluid flow, and the genesis of this type of uranium deposit.

Conceptual model construction

The conceptual model is based on the geological characteristics of the Athabasca, Thelon, and Kombolgie basins. The Athabasca and Thelon basins cover about 200,000 square kilometers in Northern Saskatchewan, Western Alberta, and the Northwest Territories of Canada, and have maximum formation ages of ca. 1730 Ma and 1753 Ma, respectively (Alexandre et al., 2009; Hiatt et al., 2003). The basement comprises Archean to Paleoproterozoic rocks, and the overlying sedimentary basin fill is represented by the Athabasca and Thelon groups (1-2 km thickness). The basin fill mainly consists of quartz-rich sandstone and conglomerate deposited in alluvial, fluvial and supratidal environments. In the Athabasca Basin, U-Pb dates of uraninite and Ar-Ar dates of syn-ore illite imply that the major uranium mineralization event began at 1600 Ma. Several subsequent remobilization events, which have been interpreted to reflect far-field tectonic events, also have been identified at 1600 Ma, ca. 1400 Ma, 1270 Ma, 1100 Ma, and 850 Ma (Alexandre et al., 2009). Studies in the Thelon Basin indicate that peak diagenesis and primary mineralization began when fluid temperature reached about 200 °C (Renac et al., 2002).

The Kombolgie Basin, the northern part of the larger McArthur Basin, is located in the Northern Territory of Australia and formed at about 1793 Ma. It is underlain by Archean and Paleoproterozoic gneisses and metasedimentary rocks. Overlying the steeply dipping basement, is the flat-lying Kombolgie Subgroup (1-2 km), which is mainly composed of sandstone and conglomerate with interlayered volcanic units. The uppermost sequence of the group is composed of distal fluvial and marine sediments that indicate a marine transgression. U-Pb and ^{207}Pb/^{206}Pb ratios of uraninite in the Jabiluka uranium deposit imply that primary uraninite precipitated at 1680 Ma, followed by remobilization at 1300, 1190, and 800 Ma. Syn-ore illite and chlorite suggest mineralization temperatures ca. 200 °C (Kyser and Cuney, 2009).

A simplified sandwich-like model was constructed to reflect the shared features of typical uranium deposits in the above three Paleoproterozoic intracratonic basins (Fig. 1). The Archean to Paleoproterozoic metasedimentary rocks and gneisses are represented by a low-permeability basement, and the overlying alluvial and fluvial sedimentary facies by a homogeneous sandstone sequence, covered by a relatively low-permeability layer. The upper boundary is treated as a fixed pore pressure and stress surface. The side and bottom boundaries are assumed to be impermeable to fluid flow. For heat transport, the top boundary is maintained at 90 °C. The bottom is assigned a value based on a geothermal gradient of 30 °C/km. The two side boundaries are insulated to heat. The base of the model is fixed vertically, but is free to move in the horizontal direction. The sides have a fixed horizontal velocity during deformation. The top is completely free to deform in both directions.

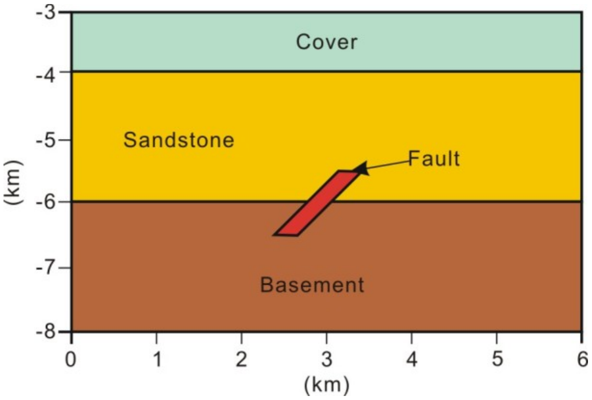

Fig. 1. Simplified hydrogeological model simulating some common features of typical unconformity- related uranium deposits.

Results

Using a strain rate of 10^{-12} s^{-1}, coupling heat transport, deformation, and fluid flow resulted in the flow of fluids out of the basement along fractured zones during tectonic compression with a maximum flow rate of 40 m/yr (Fig. 2). The temperatures in and around the fault are elevated significantly. For the same strain rate, extension results in the flow of basinal (sandstone-hosted) fluids into the basement, with a maximum flow rate of 3.9 m/yr in the fractured zones (Fig. 3). The temperature is also disturbed to some extent. Similar fluid flow patterns result when heat transport is ignored at lower strain rates (10^{-14} -10^{-13} s^{-1}). However, maximum flow rates drop significantly (< 1 m/yr). For compression, pore pressures in the low-permeability basement increase more quickly than it in the permeable sandstones, resulting in significant overpressures in the basement. In contrast, during extension, the basement becomes underpressured.

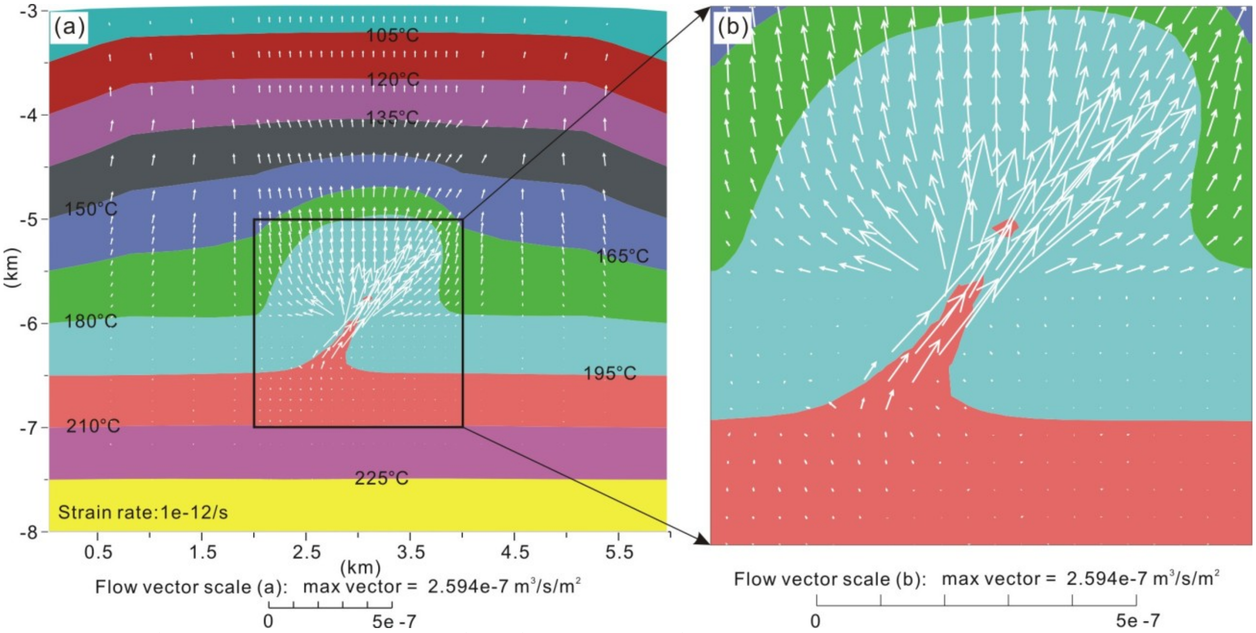

Fig. 2. Fluid-flow patterns and thermal field for coupling of compression and heat transport. The vectors represent the Darcy flux of fluid flow.

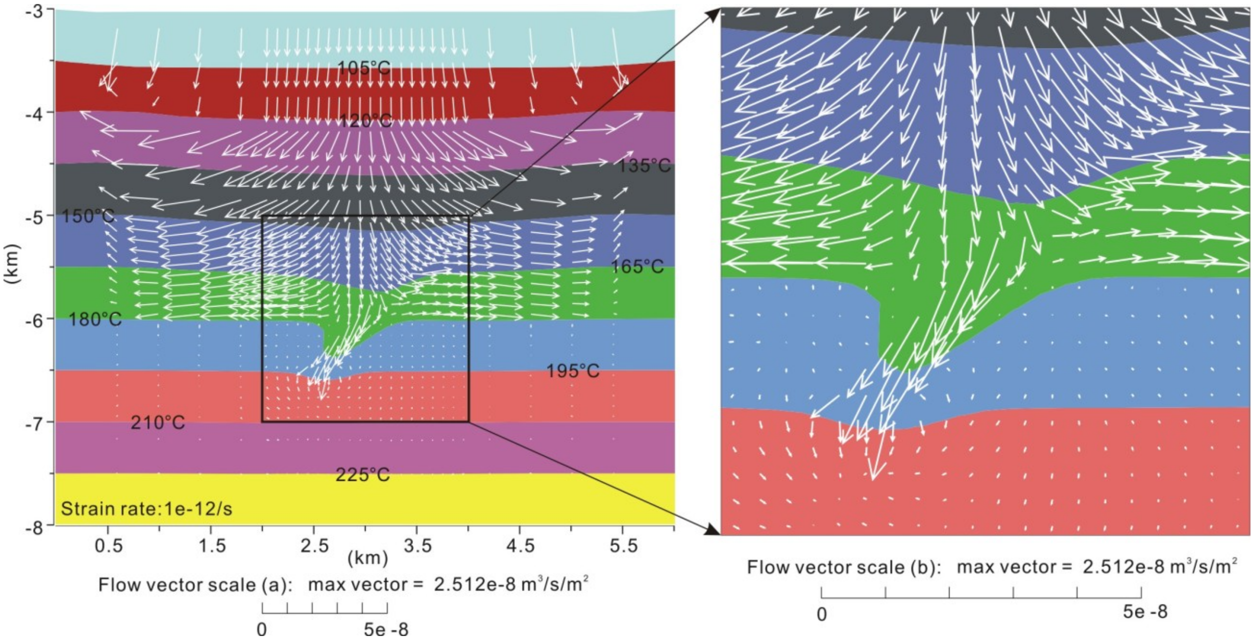

Fig. 3. Fluid-flow patterns and thermal field for coupling of extension and heat transport. The vectors represent the Darcy flux of fluid flow.

Discussion and conclusions

Cui et al. (2010) showed that thermally driven free convection may develop in the sandstone sequence under a normal thermal gradient, even for a sequence with heterogeneous permeability resulting from intercalated fine-grained sedimentary rocks. However, the free convection pattern is destroyed when tectonic deformation occurs at a realistic strain rate. Mixed convection can be obtained for an extremely low strain rate ($<10^{-14}$ s^{-1}), which means that deformation-driven flow dominates around the fault, with thermally driven flow controlling the remainder of the sequence. The specific fluid flow pattern will be determined by the relative roles of various hydraulic properties and the strain rates.

A tentative model is proposed in which oxidized basinal fluids leach uranium from the basin fill sequence during free convection in tectonically quiet periods. During tectonic compression, basement-derived reduced fluids flow up along fault structures and mix with uranium-bearing fluids in the sandstones to form sandstone-hosted deposits. Basement-hosted deposits are formed during periods of extension when oxidized uranium-bearing brines flow down faults into the basement where they may encounter reduced minerals or fluids, forming basement-hosted deposits. Thus, primary mineralization and remobilization of deposits resulted from both free thermal convection and tectonic reactivation resulting from far-field tectonic events.

Acknowledgements

The research is supported by Natural Science and Engineering Research Council of Canada (NSERC) Discovery Grants to Jianwen Yang and Iain M. Samson.

References

Alexandre, P., Kyser, K., Thomas, D., Polito, P., and Marlat, J., 2009, Geochronology of unconformity-related uranium deposits in the Athabasca Basin, Saskatchewan, Canada and their integration in the evolution of the basin: Mineralium Deposita, 44, 41-59.

Cox, S.F., 2005, Coupling between deformation, fluid pressures, and fluid flow in ore-producing hydrothermal systems at depth in the crust: Economic Geology, 100th Anniversary Volume, 39–75.

Cui, T., Yang, J., and Samson, I.M., 2010, Numerical modeling of hydrothermal fluid flow in the Paleoproterozoic Thelon Basin, Nunavut,Canada: Journal of Geochemical Exploration, in press.

Kyser, K., and M. Cuney, 2009, Unconformity-related uranium deposits, *in* M. Cuney, and K. Kyser, eds., Recent and Not-so-recent Developments in Uranium Deposits and Implications for Exploration: Short Course Series, 39: Quebec, Mineralogical Association of Canada, 161-219.

Hiatt, E., Kyser, K., and Dalrymple, R., 2003, Relationships among sedimentology, stratigraphy, and diagenesis in the Proterozoic Thelon Basin, Nunavut, Canada: Implications for paleoaquifers and sedimentary-hosted mineral deposits: Journal of Geochemical Exploration, 80, 221-240.

Hobbs, B.E., Ord, A., Regenauer-Lieb, K., and Drummond, B., 2004, Fluid reservoirs in the crust and mechanical coupling between the upper and lower crust: Earth, Planets and Space, 56, 151-1161.

Oliver, N.H.S., McLellan, J.G., Hobbs, B.E., Cleverly, J.S., Ord, A., and Feltrin, L., 2006, Numerical models of extensional deformation, heat transfer, and fluid flow across basement-cover interfaces during basin-related mineralization: Economic Geology, 101, 1-31.

Raffensperger, J. P., and Garven, G., 1995, The formation of unconformity-type uranium ore-deposits.1. Coupled groundwater-flow and heat-transport modeling: American Journal of Science, 295, 581-636.

Renac, C., Kyser, T. K., Durocher, K., Dreaver, G., and O'Connor, T., 2002, Comparison of diagenetic fluids in the Proterozoic Thelon and Athabasca Basins, Canada: implications for protracted fluid histories in stable intracratonic basins: Canadian Journal of Earth Sciences, 39, 113-132.

Sibson, R.H., 2001, Seismogenic framework for hydrothermal transport and ore deposition: Reviews in Economic Geology, 14, 25-50.