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The Ranger uranium deposit, northern Australia: Timing constraints, regional and ore-related alteration, and genetic implications for unconformity-related mineralisation

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ABSTRACT

The Ranger 1 unconformity-related uranium deposit in the Northern Territory of Australia is one of the world's largest uranium deposits and has ranked in the top two Australian producers of uranium in recent years. Mineralisation at the Ranger, Jabiluka and other major unconformity-related deposits in the Alligator Rivers Uranium Field (ARUF) occurs in Paleoproterozoic metamorphic basement rocks immediately beneath the unconformity with the Paleo- to Mesoproterozoic McArthur Basin.

The sites of uranium mineralisation and associated alteration at the Ranger 1 deposit (Number 3 orebody) were fundamentally controlled by reactivated shear zones that were initiated during the regional Nimbuwah tectonothermal event. The timing of shearing at medium metamorphic grade was constrained by ion microprobe U–Pb dating of zircons in two pegmatites, one weakly foliated (1867.0 ± 3.5 Ma) and another that is unfoliated and cuts the shear fabric (1862.8 ± 3.4 Ma). The younger age of ~1863 Ma represents the minimum age of D1 shearing during the Nimbuwah event at the Ranger 1 deposit (Number 3 orebody). Titanite within veins of amphibole-plagioclase-apatite yielded an ion microprobe U–Pb age of 1845.4 ± 4.2 Ma, which represents a previously unrecognised hydrothermal event in the ARUF. Based on previous data, retrograde hydrothermal alteration during D2 reactivation of D1 shear zones is interpreted to have occurred at ~1800 Ma during the regional Shoobridge tectonothermal event.

Detailed paragenetic observations supported by whole-rock geochemical data from the Ranger 1 deposit (Number 3 orebody) reveal a sequence of post-D2 hydrothermal events, as follows. (1) Intense magnesium-rich chlorite alteration and brecciation, focussed within schists of the Upper Mine Sequence in the Cahill Formation. (2) Silicification of Lower Mine Sequence carbonate rock units and overlying schist units, comprising quartz ± Mg-foitite (tourmaline) ± muscovite ± pyrite ± marcasite, and rare uraninite (early U1). (3) Formation of main stage uranium ore and heterolithic breccias including clasts of olivine–phyric dolerite, with breccia matrix composed of uraninite (U1), Mg-chlorite ± Mg-foitite and minor pyrite and chalcopyrite. (4) A second generation of uraninite (U2) veinlets with disordered graphitic carbon and quartz of hydrothermal origin. (5) Late-stage veinlets of massive uraninite (U3). As inferred in a previous study and confirmed herein, olivine–phyric dolerite dykes at Ranger are mineralised and chloritised, and are geochemically similar to the regional Oenpelli Dolerite. A maximum age for uranium mineralisation at the Ranger 1 deposit is therefore set by the age of the Oenpelli Dolerite (~1723 Ma).

In-situ ion microprobe U–Pb analysis of texturally oldest U1 uraninite yielded a discordia array with a $^{206}Pb/^{238}U$–$^{207}Pb/^{235}U$ upper intercept age of 1688 ± 46 Ma. The oldest individual ion microprobe ^{207}Pb–^{206}Pb age is 1684 ± 7 Ma whereas the oldest age determined by in-situ electron microprobe chemical dating of U1 uraninite is ~1646 Ma. Another sample containing both U1 and U2 uraninite yielded discordant data with a $^{206}Pb/^{238}U$–$^{207}Pb/^{235}U$ upper intercept age of 1421 ± 68 Ma. When the $^{207}Pb/^{206}Pb$ ages are considered the data are suggestive of U2 uraninite formation and possible resetting of the U1 age between ~1420 Ma and ~1040 Ma. All ion microprobe analyses of U1 and U2 uraninite indicate variable and possibly repeated lead loss. In contrast ion microprobe U–Pb dating of the third generation of uraninite (U3) yielded several near-concordant analyses and a $^{206}Pb/^{238}U$–$^{207}Pb/^{235}U$ upper intercept age of 474 ± 6 Ma. This age is supported by electron microprobe chemical ages of U3 uraninite between 515 Ma and 385 Ma.

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The new results constrain the timing of initial uranium mineralisation at the Ranger 1 deposit (Number 3 orebody) to the period ~1720 Ma to ~1680 Ma, which just overlaps with a previous U–Pb age of 1737 ± 20 Ma for uraninite-rich whole-rock samples. Our results are consistent with individual laser-ICPMS $^{207}Pb/^{206}Pb$ and chemical ages of uraninite as old as 1690–1680 Ma reported from other deposits and prospects in the ARUF.

Whole-rock geochemical data in this study of the Ranger 1 deposit (Number 3 orebody) and in other studies in the ARUF demonstrate that zones of intense chloritisation associated with uranium mineralisation experienced large metasomatic gains of Mg, U, Co, Ni, Cu and S and losses of Si, Na, Ca, Sr, Ba, K, Rb, Y and the light REE. More broadly in the ARUF, a regionally extensive illite–hematite ± kaolinite-bearing 'paleoregolith' zone in basement beneath the McArthur Basin exhibits depletion of about half of its uranium as well as major losses in Na, Sr, Pb, Ba and minor losses of Mg. These features together with new petrographic observations suggest this zone is a regional sub-McArthur Basin alteration zone produced by interaction with diagenetic or hydrothermal fluids of primary basinal origin, rather than representing a low-temperature paleo-weathering zone before the deposition of the McArthur Basin, as previously suggested.

Based on these results and a synthesis of previous work, a new multi-stage model is proposed for the Ranger 1 ore-forming mineral system that may apply to other major unconformity-related uranium deposits in the ARUF and which may be used for targeting new deposits in the region. As in most recent models, oxidised diagenetic brines within the McArthur Basin are envisaged as crucial in mobilising uranium. However, a different architecture of fluid flow is proposed involving the sub-unconformity regional basement alteration zone as a preferential source of leached uranium. Possibly driven by convection during regional magmatism at ~1725–1705 Ma, oxidised basinal brines were drawn downwards and laterally through fault networks and fractures in the regional sub-unconformity alteration zone, leaching uranium from hematite-altered basement rocks. Simultaneously within deeper and lateral parts of the hydrothermal system, Mg-metasomatism produced chloritic alteration and brines with increased acidity and silica content (from the desilicification of the basement rock), analogous to processes described in sub-seafloor hydrothermal systems. Silicification occurred locally (e.g., Ranger deposit) within upflow zones of convective systems due to decreases in temperature and/or pressure of the brines and/or CO_2 generation during carbonate dissolution. Interruptions to convection during transient regional extensional or strike-slip tectonic events resulted in generalised lateral and downwards flow of fluids from the McArthur Basin through deepened zones of sub-unconformity alteration, transferring leached uranium into reactivated shear zones within the basement. The main stage of uraninite precipitation at the Ranger deposit and elsewhere in the ARUF is proposed to have occurred between ~1720 Ma and ~1680 Ma as a result of reduction of oxidised and evolved basin-derived ore fluids during reaction with pre-existing Fe^{2+}-bearing minerals and/or mixing of the ore fluids with basement-reacted silica-rich brines.

A second, volumetrically minor but locally high-grade, stage of uraninite mineralisation was associated with hydrothermal disordered carbon and quartz of presently unknown origin. Available data suggest formation between ~1420 Ma and ~1040 Ma. Almost a billion years later at ~475 Ma, fluids capable of mobilising uranium again resulted in uraninite (U3) deposition as sparse veinlets in the Ranger deposit, representing the first documentation of uranium mineralisation of this age in the region.

1. Introduction

Unconformity-related uranium deposits are the world's most important sources of high grade uranium ore, recoverable at low cost (OECD, 2014, recoverable at <USD$40/kg U). Deposits associated with the Proterozoic Athabasca Basin in Saskatchewan, Canada, and with the northern McArthur Basin in Australia host the largest known resources of unconformity-related uranium, with global resources of this type totalling 765 000 t U (OECD, 2014; reasonably assured + inferred resource categories, recoverable at <USD$260/kg U). The Athabasca deposits occur within both the basin and the metamorphic basement rocks, and also at the unconformity itself; the highest grade ores occur at and above the unconformity, with average grades of up to 14% U (OECD, 2014). In contrast the known unconformity-related deposits in the Alligator River Uranium Field (ARUF) in Australia are hosted by Archean-Proterozoic basement of the Pine Creek Orogen (PCO) and are of generally lower grade than the Canadian counterparts. Nevertheless, total uranium resources are large: the undeveloped Jabiluka deposit contains 141 640 t U_3O_8 @ 0.48% U_3O_8 (as at 31 December 2014, Energy Resources Australia announcement, 6 February 2015; cutoff 0.15% U_3O_8, reserves plus resources), and the Ranger 1 deposit is one of the largest uranium deposits in the world, having a total endowment (past production plus remaining resource) of 130 000 t U (MODAT, 2011, www.nt.gov.au). Recent exploration including >47 km of drilling since 2009 in the Ranger 3 Deeps zone has identified a new resource of 34 867 t U_3O_8 @ 0.28% U_3O_8 (as at 31 December 2014, Energy Resources Australia announcement, 6 February 2015; cutoff 0.15% U_3O_8, measured + indicated + inferred resources). A major challenge for exploration and mining companies is the discovery of high grade uranium ores within the ARUF, of similar quality to deposits in the Athabasca region.

Targeting of unconformity-related uranium deposits and higher grade mineralisation can benefit from an understanding of the processes that resulted in uranium deposition, not only at the deposit scale but also within the regional- to crustal-scale 'mineral system' (Wyborn et al., 1998). This comprises the full set of geological conditions leading to a coincidence in time and space of (1) source(s) of uranium and other ore-forming components such as mineralising fluids, (2) energy source(s) to 'drive' hydrothermal fluid flow, (3) structural architecture favourable for the transfer of fluids and for the transport and deposition of large quantities of uranium, and (4) gradients in physico-chemical conditions favourable for the deposition of uranium ores. The identification and mapping of each of these necessary components of the mineral system will allow predictive targeting of mineralisation, potentially in areas not previously known to be mineralised.

A general consensus has emerged for the involvement of basin-derived brines in the formation of unconformity-related uranium deposits, building on the pioneering 'diagenetic-hydrothermal' model of Hoeve and Sibbald (1978). There is less agreement on the sources of uranium in both the basin-hosted and basement-hosted deposits (Kyser and Cuney, 2009), with some advocating a basin source (e.g., Wilde and Wall, 1987; Wilson and Kyser, 1987; Fayek and Kyser, 1997; Polito et al., 2004, 2005, 2011) and others proposing a basement rock source of uranium (e.g., Hecht and Cuney, 2000; Derome et al., 2003; Richard et al., 2010; Mercadier et al., 2012, 2013a). Published