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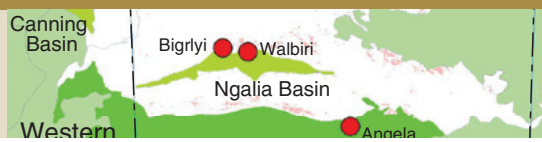
Association of large sandstone uranium deposits with hydrocarbons

The geology of uranium deposits in Kazakhstan points to similar deposits in Australia



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Sandstone uranium deposits account for approximately 30% of annual global production, largely through in situ leach (ISL) mining. Most of this production has come from deposits in the western United States, Niger and Kazakhstan. In Australia, sandstone-hosted uranium is being produced from the Beverley deposit in the Frome Embayment of South Australia, and a second ISL mine is under development at Honeymoon in the same region.

Such deposits form where uranium-bearing oxidised groundwaters moving through sandstone aquifers react with reducing materials. The locations of ore zones and the sizes of mineral deposits depend, among other factors, on the abundance and reactive nature of the reductant. Hence, the nature and abundance of organic material in the ore-bearing sedimentary sequence may be of critical importance for the formation of sandstone uranium deposits.

In sandstones rich in organic material (containing debris of fossil plants or layers of authigenic, or in situ generated, organic material) the organic matter either reduces uranium directly with bacteria as a catalyst, or through the production of biogenic hydrogen sulfide (H_2S: Spirakis 1996). In sandstones relatively poor in organic material, it has been proposed that the reduction is caused either by H_2S (biogenic as well as nonbiogenic) produced from the interaction of oxidised groundwater with pyrite in the sandstone aquifer (thiosulfate produced initially by oxidation of pyrite breaks down to form reduced sulfur), or from the introduction of reduced fluids/gases (H_2S, hydrocarbons or both) along favourable structures (Spirakis 1996).

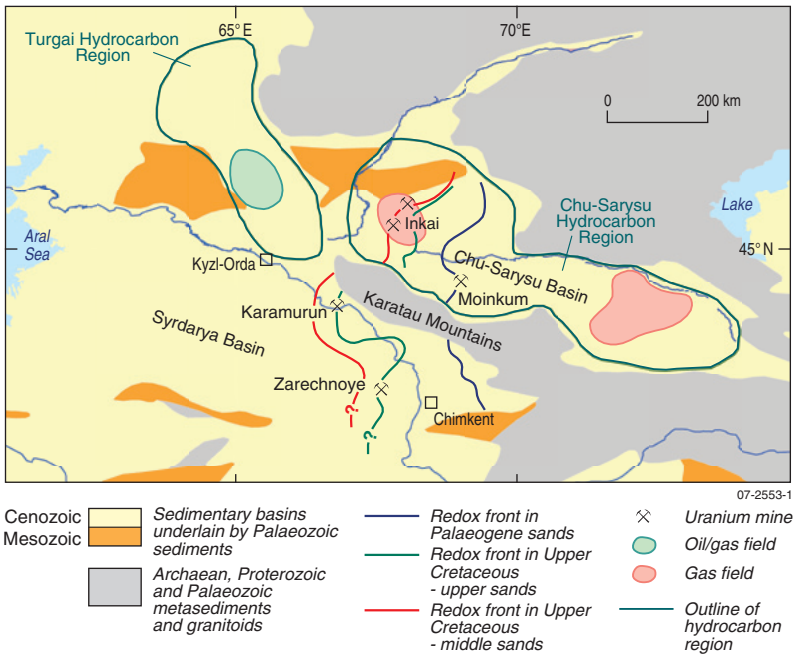

Figure 1. Regional geology of Chu-Sarysu and Syrdarya basins, southern Kazakhstan. Geological data plotted from the Generalized Geological Map of the World (1995), Geological Survey of Canada Open File 2915d. Boundary of the hydrocarbon basins and location of oil and gas fields in the underlying Permian rocks from a map produced by Blackbourn Geoconsulting (http://www.blackbourn.co.uk/databases/hydrocarbon/chusarysu.html).

This paper outlines the geology of the world-class sandstone uranium deposits in the Chu-Sarysu and Syrdarya basins in the south-central portion of Kazakhstan, which are hosted by sandstones relatively poor in organic matter (figure 1, table 1). We highlight the crucial role that hydrocarbons appear to have played in the formation of these and other large sandstone type uranium deposits. Based on the model developed, we conclude that there is considerable potential in Australia for the discovery of large sandstone-hosted uranium mineralisation, including in little explored regions underlain by basins with known or potential hydrocarbons.

Table 1 Uranium resources, organic carbon and sulfides in basins hosting major resources of sandstone uranium deposits

Basin/sub-basin	Resources ('000 tonnes U_3O_8)	Organic carbon (wt%)	Iron sulfide (wt%)
Chu-Sarysu and Syrdarya	1340[a]	< ~ 0.03–0.05[b]	0.1[c]
Callabonna (Frome Embayment)	41.2[d]	< 0.05 to 0.5[e]	Traces[e]
Wyoming	320[f]	0.5[c]	1 to 4[c]
South Texas	45 to 80[g]	<0.16[h]	0.5 to 4[h]

a Fyodorov (1999); b Petrov (1998); c Fyodorov (1996); d Ozmin database, Geoscience Australia (2007); e Heathgate Resources (1998); f after de Voto (1978); g Dhalkamp (1993); h Goldhaber et al (1978)

The geological setting in Kazakhstan

The Chu-Sarysu and Syrdarya basins of Kazakhstan are components of a large artesian basin that was split into two main components following the Pliocene uplift of the Karatau Mountain Range (figure 1). The basins are filled with thick sandstone aquifers capped by impermeable shaly beds. Mineralisation, often as roll fronts, is hosted by sands of Upper Cretaceous and Palaeocene–Eocene age.

The Chu-Sarysu Basin is more mineralised than the Syrdarya Basin and contains larger uranium deposits, which are hosted by a Late Cretaceous – Palaeogene age multicoloured clay–gravel–sandstone sequence deposited in a continental environment. The large deposits include Inkai, Moinkum, Karamurun and Zarechnoye. In the Syrdarya Basin, the host is a grey clay – sandstone sequence formed in coastal-marine and continental conditions (Petrov 1998).

The roll fronts display mineral and geochemical zoning typical of oxidation–reduction fronts associated with sandstone uranium deposits elsewhere. Hydroxides of iron dominate the oxidation zone, whereas the reduced zones are dominated by iron sulfides (pyrite and marcasite). The uranium zone is enriched in rhenium, zinc, copper, silver, cobalt, molybdenum, nickel and vanadium. Significant enrichments of selenium occur towards the contact with the zone of reduction.

"Based on the model developed, we conclude that there is considerable potential in Australia for the discovery of large sandstone-hosted uranium mineralisation."

The ore zones extend for 20 to 30 kilometres along the redox front; in plan, they form ribbons 50 to 800 metres wide (rarely, 1.7 kilometres). In cross-section, the zones are asymmetric roll-fronts, tabular bodies and lenses. Thickness varies from five metres to more than 25 metres. Uranium mineralisation occurs as coffinite and pitchblende, which are finely dispersed in the clay matrix and also infill cavities in sandstone (Petrov 1998). The depth of uranium ore varies from 100 metres to more than 800 metres (Fyodorov 1996).

The source of uranium in the deposits is not clear. It could have been derived from Ordovician and Silurian metasediments and granites exposed in the Tyan-Shan Ranges along the southeastern flanks of the basin, which also provided the detrital material for the sedimentary sequence hosting mineralisation. Uranium-bearing hydrothermal vein deposits hosted in pre-Mesozoic metasediments along the northeastern flanks of the Chu-Sarysu Basin could also have been a source (Petrov 1998). Further uranium could have been contributed from devitrification of volcanic tuff interbedded with Palaeocene/Eocene sands.

Lead–lead isotope model ages suggest that mineralisation occurred in three more or less continuous stages starting from Late Oligocene – Middle Miocene and continuing into Late Pliocene to Quaternary time (Mikhailov and Petrov 1998). Tectonic reactivation during

the Late Oligocene – Middle Miocene created palaeogeographic conditions favourable for large-scale groundwater flow from the palaeo Tyan-Shan region in the southeastern flanks of the basin.

The regional extent and general distribution of the redox fronts in the basins suggests that the palaeo-groundwater flow direction was predominantly from the southeast to the northwest. Groundwaters probably entered permeable aquifers adjacent to the Tyan-Shan uplands (Petrov 1998) and flowed towards discharge zones in the general region of the Aral Sea.

Late Pliocene – Quaternary ages of mineralisation coincide with intensive tectonic activity associated with orogenic movements in the Tyan-Shan and the uplift of the Karatau Mountains, along a pre-existing regional fault, which created the present-day hydrodynamic regime. Groundwater flows associated with the Karatau uplift only caused minor changes in the configuration of the mineralised regional redox fronts created in the Late Oligocene – Middle Miocene (Petrov 1998).

Although organic material in the ore-bearing grey sandstones is quite low (generally <0.03–0.05%; table 1), Petrov (1998) believes that it was enough (with a minor contribution from iron sulfides) to produce large sandstone uranium deposits. Petrov ascribes the lack of direct correlation between uranium and the concentration of organic material to coalification of organic material, which caused loss of active organic reductants such as waxy bitumen and humic acids.

Chu-Sarysu oil and gas basins

The Late Cretaceous to Palaeogene continental and marine sedimentary sequence that hosts world-class sandstone uranium deposits is underlain by a Palaeozoic sequence up to five kilometres thick containing oil and gas (figure 2; Bykadorov et al 2003). The Chu-Sarysu hydrocarbon basin is made up of two sequences: lagoonal to marginal-marine salt-bearing strata of Famenian – Early Carboniferous age; and alluvial-lacustrine red-beds of Middle Carboniferous – Permian age. The latter include 500 metres of Permian evaporites. Visean and Early (pre-salt) Permian sandstones host minor volumes of gas. The southeastern part of the basin contains hydrocarbon source rocks and also hosts the principal oil and gas fields. Famenian – Early Carboniferous marls and black shales and Permian bituminous marls with high total organic carbon may be an additional source, with Permian salts acting as a regional cap (Bykadorov et al 2003).

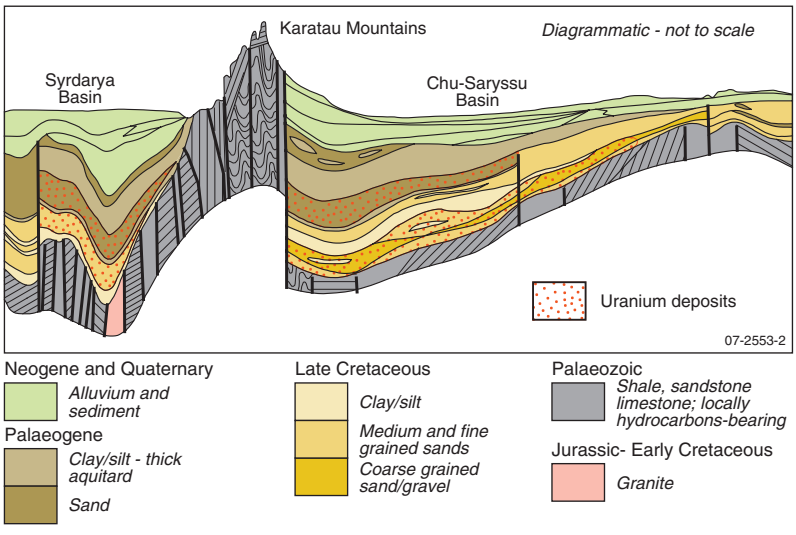

Figure 2. Cross-section of Chu-Sarysu and Syrdarya basins (looking northwest) (Yazhikov 1996).

Aubakirov (1998) suggested that the uranium mineralisation formed at a geochemical trap created by an influx of reduced fluids/gases (hydrocarbons and H_2S) along relatively deeply penetrating structures. Chemical analyses of drill core samples through the ore zones show that hydrocarbon gases have accumulated along the redox front. Some authors consider that this accumulation of hydrocarbon gases facilitated large-scale ore formation over extensive redox boundaries (Fyodorov 1999), although the detailed geochemical (including

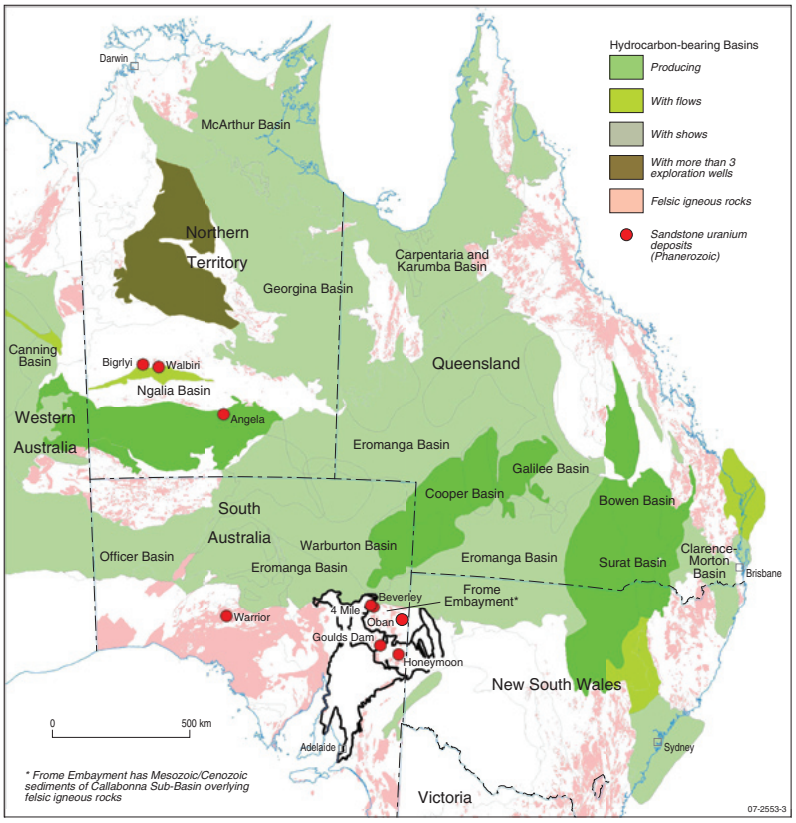

Figure 3. Maps showing hydrocarbon-bearing onshore basins of Australia and Archaean/Proterozoic terranes with uranium-rich felsic rocks. Data for hydrocarbon-bearing basins from Geoscience Australia's dataset of Sedimentary basins. Outcropping felsic rocks (NSW, Northern Territory, Queensland, Tasmania, Victoria) from Geoscience Australia's 1:1 000 000 Surface Geology of Australia map. Felsic rocks in SA and WA extracted from the solid geology maps of SA and WA (Solid Geology of South Australia, 2006 and 1:500 000 Interpreted Geology Map of Western Australia, June 2001) respectively.

sulfur and carbon isotopic) studies required to define more precisely the role of hydrocarbons and/or H_2S in the Chu-Sarysu and Syrdarya basins have not been conducted.

Based on the observed features, we propose that the one condition conducive to formation of the large Kazakhstan sandstone uranium deposits (table 1) is the organic-poor nature of the highly permeable sands in the large Cretaceous and younger artesian basin, which ensured sustained flow of uranium-bearing oxidised groundwater in the aquifers. The other favourable condition would have been the localised availability of active reductants in the form of hydrocarbon gases (including H_2S) leaking from Permian hydrocarbon reservoirs (figure 1). A rapid and localised reduction might be critical to form relatively large deposits, and tectonic activation of faults in the Late Oligocene – Middle Miocene could have facilitated ingress of the necessary hydrocarbon gases, particularly at the margins of the hydrocarbon reservoir where the seal was less effective. These conditions resulted in the location of roll fronts at distances of 300 to 350 kilometres from the uranium basin margin.

In other roll-front systems (such as in the Wyoming Basin), oxidised waters encounter reducing materials distributed through the aquifer and the redox roll front migrates progressively down dip. Under these conditions, the potential for very large deposits is considered lower and the deposits tend to occur within about 60 kilometres of the margins of the sandstone uranium basins.

Examples in China and Texas

The close spatial association between sandstone uranium deposits and hydrocarbon-bearing basins observed in the Chu-Sarysu Basin is not unique. In recent years, sandstone uranium deposits closely associated with hydrocarbon-bearing basins have been identified in the Ordos and Songlio basins in China (for example, Huang Xian-fang et al 2005).

Further afield, in the Texas Uranium Region (Texas Coastal Plain), uranium mineralisation in organic-poor sandstones has been attributed by several researchers to the influx of H_2S along faults from hydrocarbon reservoirs at depth (Reynolds and Goldhaber 1978).

Implications for Australia

Australia holds roughly 30% of global uranium resources

recoverable at <US$80/kg U (Reasonably Assured plus Inferred Resources). Over 90% of those resources are in Olympic Dam, a hematite breccia complex (also known as iron oxide – copper – gold – uranium) deposit, and in unconformity-related uranium deposits. Only about 2% of Australia's known uranium resources are in sandstone deposits, despite apparently favourable geological settings for this style of uranium mineralisation.

Organic-rich sands of the Eyre and Namba formations (Cainozoic) are hosts for sandstone uranium deposits in the Frome Embayment and are a focus for ongoing and successful uranium exploration.

However, geological settings similar to that of the Chu-Sarysu and Syrdarya Basins can be identified in a number of hydrocarbon-bearing basins in Australia. For instance, hydrocarbon reservoirs in the Cooper Basin underlie several sandstone aquifers in the Eromanga Basin (figure 3). This implies that the organic-poor parts of aquifers further from basement outcrops should be evaluated, as they could contain uranium mineralisation where hydrocarbons or H_2S leaked from hydrocarbon reservoirs.

In summary, based on the model (figure 4) developed in this paper for large sandstone uranium deposits and the information presented in figure 3, we conclude that there is considerable potential for new, economically significant, sandstone-type uranium systems in Australia, particularly in the following areas:

- northern Frome Embayment (Eromanga Basin adjacent to Mt Painter and Willyama/Olary inliers)
- Lake Eyre area (Eromanga, Arckaringa, Arrowie and Warburton Basins in proximity to Mt Painter and Peake and Denison inliers)
- Eromanga, Cooper, Warburton and Galilee Basins
- Surat, Bowen, and Clarence-Morton Basins
- Carpentaria and Karumba Basins adjacent to Mt Isa Inlier and Georgetown inliers
- Georgina Basin
- Amadeus and Ngalia Basins
- Officer and Canning Basins
- McArthur Basin.

Within these basins, areas at the margins of the hydrocarbon cap-rocks and near to active structures would be of particular interest.

Reduction of uranium-bearing waters by hydrocarbons should typically result in the formation of carbonates within and near ore zones. An Australian example of such diagenetic carbonate zones (without associated uranium mineralisation) has been described for the hydrocarbon-bearing Vulcan sub-basin (O'Brien and Woods 1995).

Large sandstone uranium systems containing relatively massive zones of carbonates may be visible on seismic sections, as is the case in the Vulcan sub-basin. Other datasets useful for the exploration of sandstone uranium systems include oxidation state of groundwaters and sandstones from hydrogeochemistry; colour of sandstone (and other indicators of oxidation state); distributions of hydrocarbon cap rocks; porosity and permeability of sandstone aquifers; and active structures.

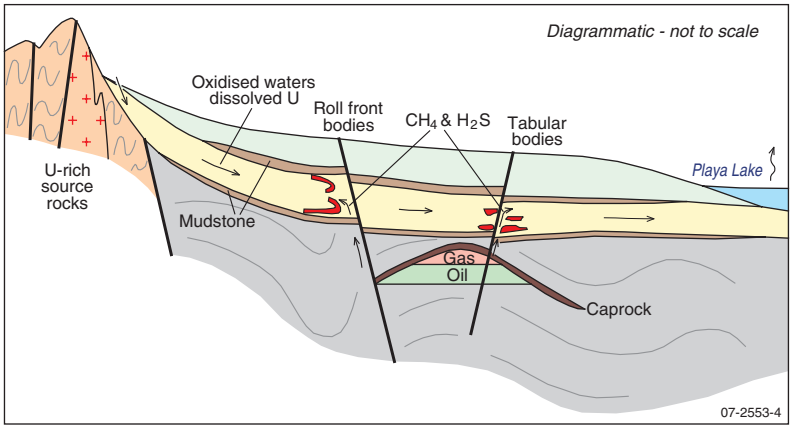

Figure 4. Diagrams showing proposed model. Uranium is carried in oxidised groundwaters and reduced by hydrocarbons and/or H_2S released from the underlying oil and/or gas field. Both roll-front and tabular ore bodies can result from the process. During ore deposition hydrocarbons are often oxidised to form carbonates.

Conclusions

We propose that potentially large sandstone uranium mineralisation is most likely to occur where three criteria are met:

- hydraulic connections to uranium-enriched source rocks
- presence of permeable sandstone aquifers, with impermeable rocks above and below that seal the aquifer
- hydrocarbon accumulations in the sequence underlying the aquifers together with features that could have facilitated migration of hydrocarbon gases into the uraniferous aquifer, in particular areas at the margins of hydrocarbon cap-rocks and where there has been reactivation of structures.

This model has been applied to Australia at regional scale, leading to the conclusion that there is considerable scope for discovery of major sandstone uranium mineralisation of the general type being mined in Kazakhstan.

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