

Exploration strategies for Uranium deposits

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ABSTRACT: Although exploration strategies for uranium differ slightly for each deposit type, radiometrics, geophysics, and drilling are the major tools used. However, certain aspects common to all uranium deposits should be exploited to refine exploration. These include the timing of alteration and mineralizing systems, the nature of the fluids involved in each, the likely source of uranium, and the precipitation mechanism for the ore and alteration minerals. How these can be integrated into exploration is exemplified by comparing and contrasting results from unconformity-related and sandstone-hosted deposits.

KEYWORDS: *uranium, geochronology, basins, exploration, geochemistry*

INTRODUCTION

Exploration strategies for various types of U deposits vary depending on the type of deposit, but there are some general aspects critical to all types of U deposits. Although often considered academic, these should be part of advanced exploration efforts and include; (1) timing of the mineralizing and alteration processes, (2) nature of the fluids involved, (3) source of the U, and (4) the nature of an effective trapping mechanism. These aspects are often overlooked or trivialized relative to more classical aspects such as tectonic or structural setting.

(1) Timing of the mineralizing and alteration events is required in exploration so that the geologic, chemical and physical environment conducive to mineralization at the critical time in the evolution of an environment can be realized. Determining the age of U deposits is not straightforward (e.g., Chipley *et al.* 2005), but precise dating of uranium minerals and associated gangue minerals of known paragenesis, and integration of age data with other geologic factors render interpretation of geochronological data meaningfully for exploration. Without an idea of both the relative and absolute age of the mineralization, and both the alteration and

the host, strategies cannot evolve beyond prospector-driven exploration.

Effective exploration in any deposit requires detailed knowledge of the time-space relationships. For example, magmatic-related deposits form after advanced differentiation of peralkaline, post-orogenic parent magmas to allow extreme U enrichment in the latest magma intrusions and related magmatic fluids. In collision zones, U deposits related to peraluminous leucogranites require melting of the crust, which is facilitated by crustal thickening at an appropriate time during convergence. Metasomatic U deposits are associated with metamorphism during rapid uplift of an orogen, almost exclusively during the Proterozoic. Unconformity-related deposits require 75-100 m.y. after basin formation to allow chemical and thermal evolution of the fluids.

The timing of events that have subsequently affected the ores can also reveal when elements such as radiogenic Pb have been mobilized from the deposits and moved into the surrounding environment. These elements would elevate element concentrations in the surrounding environment, with gradients in concentrations as vectors to the deposits (Holk *et al.* 2003, Kister *et al.* 2004).

(2) Knowledge of the nature of the fluids involved, particularly their origin, temperature, pressure, oxygen fugacity, and chemical composition, is needed to identify the correct environment in which to explore. For example, most highly evolved alkaline intrusives do not host U deposits because they do not evolve to concentrate U in the last fluids, thereby necessitating evolution to magmatic fluids rich in U. Most areas of albitization do not host deposits because there was no reductant to trap the U. Diagenetic brines are involved in the genesis of unconformity-related uranium deposits, but most areas in basins with the appropriate geology and structure conducive to the ore-forming process are devoid of any significant U mineralization because reducing fluids were not present at the appropriate times in these areas. Most sandstone-hosted deposits occur in meanders of paleostreams where organic detritus could accumulate, but most such areas do not host ore because groundwaters either did not flow or did not carry U. Understanding why barren areas that should have ore, but do not, requires knowledge of the physical, chemical, and temporal characteristics of the fluids required to form various types of U deposits.

(3) The source of the U for many deposits is in units that have aberrantly high U contents, such as in volcanic glasses in the case of tabular deposits or in highly differentiated alkaline intrusions in the case of some magmatic-type deposits. Enrichment of U in the source region of basin-hosted deposits certainly increases the probability that a deposit could form (e.g., McNeal *et al.* 1981), as does the availability of U in the source region. Uraninite represents the most easily leachable U (sourced by oxidized fluids). Further, U is unlikely to be released from refractory minerals such as zircon unless they become metamict, which requires time. In sandstone-hosted deposits, unstable volcanic glasses with high U contents, mainly of peralkaline composition, make ideal sources because the U can be effectively mobilized.

(4) Trapping of U is a critical process for the generation of a deposit, with gradients in redox environments a necessity. For example, roll-front deposits best exemplify the gradients that occur in U mobilization and fixation. Deposits in the Paleoproterozoic Franceville Basin have characteristics very similar to unconformity-related deposits, but they occur at a redox boundary between oxidized sandstone and black shales within the basin. Unconformity-related deposits are normally associated with graphite, sulfide or a reducing fluid from the basement. For high temperature environments, such as the Rössing deposit, redox boundaries are represented by graphite-sulfide-rich metasediments. In these and other deposits, carbon appears to be an effective reductant, but there are alternatives such as sulfides and ferrous iron. Graphite, which is intimately associated with most unconformity-related deposits, is geochemically inert and therefore is unlikely to be an effective reductant unless it is modified to a more reactive form.

Although specific tectonic environments, structural settings and lithologies are required for all U deposit types, none of these are definitive indicators of mineralization because most of these settings, structures and lithologies do not host deposits. Thus, they are required for the deposits to form, but are not definitive indicators of mineralization. In effect, the only definitive indicators are geochemical, both in terms of U concentration and in the associated elements.

EXPLORATION STRATEGIES

With few exceptions, there is a paucity of published examples of exploration strategies for U, especially during the past 40 years. This would suggest that either there has been minimal advancement in exploration techniques or that this knowledge is resident in the geologists or companies that survived the drought in uranium exploration. The latter is unlikely given the time and personnel that have passed, and there have been advances in exploration for U other than drilling, but

these have been largely unnoticed. Differences and similarities in exploration strategies are conveniently illustrated by comparing how exploration is normally done for unconformity-related and sandstone-hosted deposits.

Unconformity-related deposits

Exploration for unconformity-related deposits is based firstly on Proterozoic red-bed basins overlying basement complexes and source regions characterized by high U contents. Given this criteria alone, there are nearly 200 basins that would qualify. Graphitic metasedimentary units within the basement complex are desirable, but not necessary, as exemplified by the Nabarlek deposit in the Northern Territory, Australia (Polito *et al.* 2004). Repeated brittle reactivations of ductile structures, normally from far field tectonic events, that may offset the basal unconformity and were foci for fluid flow are required.

Lithogeochemical and mineralogical haloes around unconformity-type uranium deposits can expand the size of drill targets (e.g. Quirt 1985). The ratio K_2O/Al_2O_3 can be useful in delineating hydrothermal illite distribution in the sandstone, and anomalously high boron haloes, corresponding to dravite alteration are also characteristic of these deposits, although dravite is not paragenetically related with the ore-forming process. Uranium, Ni, As, and Co are generally of more limited use because their haloes are restricted to a few tens of metres. The complexity of the basement lithology inhibits the use of individual elements as alteration guides other than in the intensely altered zone (Sopuck *et al.* 1983).

Clay minerals are ubiquitous up to hundreds of metres from hydrothermal U mineralization, and often there is zoning in the type of alteration minerals (Hoeve & Quirt 1984). These can be mapped with remote sensing that can detect in the visible and the middle-infrared sections of the electromagnetic spectrum (Earle *et al.* 1999). The two oxidation states of U and Fe have been proposed to map bleached

alteration zones associated with uranium mineralization using multispectral sensors like Landsat ETM+ (Rajesh 2008).

Lake water and sediment geochemistry and radiometric prospecting are significant tools in early regional exploration for U deposits in Canada (Cameron 1980). The development of anomalies in lakes is a two-stage process wherein U-rich detritus is transported down-ice from the mineralized source and then the metal is dispersed in solution from this detritus into the lakes. Ground-water samples collected from boreholes tens of metres from unconformity-related uranium mineralization have high levels of U, Ra, Rn, and He (Earle & Drever 1983). However, Rn and He distributions can be greatly affected by variations in permeability of the rocks and are frequently ineffective tools to detect buried mineralization (Butt & Gole 1985).

Biogeochemistry has been developed for uranium exploration during the 1980s (Dunn 2007). For example, spruce twigs indicate that tree roots can extract anomalous U from ground water and reflect deposits at 300m depth.

The mainstay of exploration geophysics for all types of U deposits is gamma-ray spectroscopy used in airborne surveys, down hole logging and on outcrops using hand held units. The former is normally collected as part of airborne magnetic surveys with magnetics used to reveal the general geology. Airborne gamma-ray spectrometry directly measures K, eU, and eTh, but only in near surficial material.

Improved magnetotelluric methods have detected deep conductors and shallow alteration zones in the search for deep unconformity-related deposits (Farquharson & Craven 2008). Clay-rich, quartz-corroded quartz-arenite has relatively low resistivity, whereas quartz-rich silicified zones are characterized by high resistivity. Although expensive, 3D seismic has been used to image details of basement topology and more favourable areas for drilling.

Sandstone-hosted deposits

Uranium ore deposits in the Grants

Mineral Belt, New Mexico, occur in fluvial sandstones in the Jurassic Morrison Formation where U is concentrated by dark gray to black humate derived from decaying vegetation. The ores vary greatly in size and shape, generally occur in clusters, and often are difficult targets for drilling. Exploration is done primarily by drilling, delineating favourable ground on a wide-spacing and then using closely spaced drilling in mineralized areas. Criteria for favourable areas includes the presence of a host sandstone, anomalous U contents, dark colour of host rock, presence of carbonaceous matter, and position of an area with respect to mineralized trends (Fitch 1979).

Analysis of groundwater can be a useful strategy for regional exploration for U in the reduced sediments in palaeochannels, although multi-element data are required. Lead isotopes can be used to confirm the groundwater interpretations (Dickson & Giblin 2007). If reduction of U by bacteria is an effective mechanism for formation of U deposits in palaeochannels, then microbial induced geochemical signals, such as carbon isotopes or enhanced mobile metals, should indicate favourable areas.

Geochemical detection of uranium deposits in sandstone-type deposits depends on the geochemical behavior of U and pathfinder elements (Rose & Wright 1980). Uranium is dispersed under oxidizing conditions but is immobile under reducing conditions. Adsorption on freshly precipitated Fe-oxides and certain types of organic matter also limits dispersion unless high concentrations of CO_3^{2-} or other complexers are present. Thorium accompanies U in most plutonic processes, but the two elements are separated under oxidizing conditions. Possible pathfinder elements associated with U in sandstone-type deposits include S, V, Mo, Se, As and at some deposits Cu, Ag, Cr, Pb, Zn, Ni, Co, Re, Be, P, Mn, and rare earths, plus He, Rn, and other radioactive decay products.

Most uranium deposits in sedimentary rocks are associated with geochemical provinces enriched in U and Th or with U-

rich intrusives or volcanic rocks, although the deposits may be separated by tens of kilometres from these U-rich source rocks. Weak regional U and Th anomalies in sediments containing U deposits may be present. Anomalies in U, Se, Mo, V, As, He, Rn, and other pathfinder elements in rock and in ground and surface waters can furnish geochemical guides to ore, as can thermoluminescence (Hochman & Ypma 1984), Pb, S and C isotopes, and textures of Fe and Ti oxides.

CONCLUSIONS

Because U deposits are geochemical anomalies, they are best discovered using strategies that integrate geochemistry as a significant part of the exploration repertoire. Exploration for U deposits, as with any type of deposit, requires the integration of geology, geophysics and geochemistry and must embrace new technologies and research results to be effective and competitive. Although "serendipity" will always be a factor, exploration must be more purposeful, especially as the need to find deposits undercover becomes more urgent. The last boom period was witness to limited success and in predominately brownfield areas. We should prepare ourselves for the next boom by refining models and finding key factors that promote formation of large deposits and the physical and chemical indicators of areas where deposits reside.

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