

Cainozoic palaeochannel-hosted uranium and current exploration methods, South Australia



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Introduction

Exploration for sedimentary uranium deposits in South Australia commenced in the late 1960s, with a focus on Cainozoic sediments adjacent to regions of uranium-enriched Proterozoic igneous rocks in the Gawler Craton and Curnamona Province (Curtis, Brunt and Binks 1990). A rapid increase in uranium exploration followed the discovery of the Beverley deposit in 1969 (Yates and Randell 1994; McKay and Mieztis 2001). This resulted in the further discovery of several small but significant resources of uranium in Cainozoic sediments (Fig. 1). In 1999

the Beverley deposit was developed using in situ leach technology. The Honeymoon deposit is currently in final stages of feasibility and deposits at Gouls Dam and Oban are at an advanced stage of evaluation. The current high level of interest in uranium exploration, targeting Cainozoic sediments in South Australia, reflects the present high price for uranium, the vast areas of Cainozoic sediments with high potential to host uranium, a proactive government policy for uranium development, and recent success with discovery of new high-grade mineralisation at the Four Mile deposits near Beverley.

Uranium deposit styles

Uranium deposits can be classified into 15 major categories based on their geological setting (Table 1). The term 'palaeochannel-related' uranium deposits probably encompass three of these categories — sandstone, surficial and lignite. Uranium resources in sandstone and surficial deposits rank second and sixth, respectively, in economic significance worldwide (Table 1). While palaeochannel-related uranium deposits are regarded as significant in South Australia, the bulk of Australia's uranium resources are contained within deposits of the categories unconformity-related (e.g. Pine Creek Orogen, Northern Territory) and breccia complexes (e.g. Olympic Dam, South Australia). The Gawler and Curnamona regions in South Australia are highly prospective for a range of uranium deposit styles, in addition to 'palaeochannel deposits' (e.g. Fabris 2004; Cooper and McGeough, 2006; Fairclough et al. 2006).

Sandstone deposits

Sandstone uranium deposits — defined as an epigenetic concentration of uranium minerals (generally uraninite (UO₂) or coffinite (USiO₄)), typically hosted by fine- to coarse-grained sediments deposited in fluvial, alluvial, lacustrine or marginal marine environments — constitute about 18% of world uranium resources (e.g. United States, Niger and Kazakhstan; Finch and Davis 1985; McKay and Mieztis 2001).

Based on the shape of the orebody and relationship to the depositional or structural environment, sandstone uranium deposits can be subdivided into three types (these may be gradational into each other): tabular, roll-front and tectonic-lithologic (Dahlkamp 1993). Tabular and roll-front mineralised bodies form along the contact of sand and intercalated clay horizons and at palaeochannel margins, while tectonic-lithologic deposits may occur in sandstones adjacent to a permeable fault

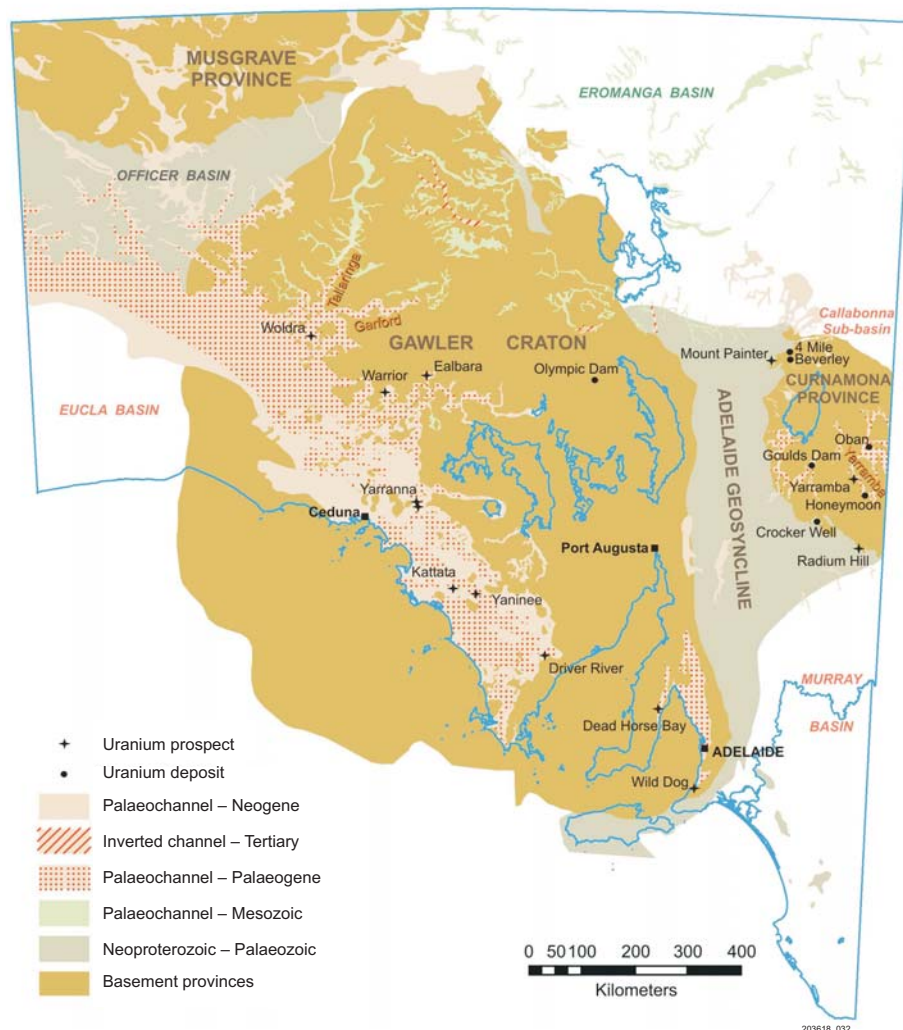


Figure 1 Major palaeochannel and Tertiary coastal barrier deposits in South Australia showing selected uranium deposits and prospects.

zone. Precipitation of uranium minerals in most tabular deposits is thought to begin shortly after sedimentation and burial. Mineral detritus and rock fragments derived from weathered bedrock are deposited along with channel sediments. The uranium is leached under oxidising and slightly acidic conditions and is mobilised in groundwater moving through the sediments, with mineralisation commonly accompanying diagenesis of the sediments. In roll-front deposits uranium is introduced into the host rocks

by oxidising waters after diagenesis (Finch and Davis 1985).

Uranium mineralisation results from the interaction of uranium-rich oxidising fluids and reduced lithologies (i.e. at redox fronts; Fig. 2). Sediments in close proximity to the redox boundary typically show yellow to orange colouration resulting from iron oxyhydroxide staining on the oxidised side of the redox boundary, changing progressively towards darker tones within reduced sediments.

These alteration zones around ore are associated with elevated radioactivity.

The main controlling factor on the location of uranium ore is the interplay of sedimentary facies and the proportion of reducing agents (e.g. carbonaceous matter, sulfides, hydrocarbons and interbedded ferromagnesian-rich basic volcanics).

Surficial deposits

Surficial uranium deposits are broadly defined as young (Cainozoic), near-surface uranium concentrations within sediments and soils, although they also occur in peat bogs and karst caverns (McKay and Mieizitis 2001). Uranium mineralisation is typically carnotite ($K(UO_2)_2(VO_4)_2 \cdot 3H_2O$) and is commonly cemented by secondary minerals including calcite, gypsum, dolomite, ferric oxide and halite. Uranium deposits in calcrete (calcium and magnesium carbonates) are the largest of the surficial deposits. These usually form in regions where deeply weathered, uranium-rich granites occur in a semi-arid to arid climate (Fig. 3). Examples from Western Australia occur in valley-fill sediments along Tertiary drainage channels (e.g. Yeelirrie) and in playa lake sediments (e.g. Lake Maitland). These overlie and are adjacent to Archaean granite and greenstone basement of the northern Yilgarn Craton that provide a source of vanadium necessary to form carnotite.

Table 1 Types of uranium deposits and their economic significance

Deposit style	Economic significance	
	Australia	Worldwide
Breccia complex	1	3
Unconformity-related	2	1
Sandstone	3	2
Surficial	4	6
Metasomatite	5	7
Intrusive	6	5
Quartz-pebble conglomerate	7	4
Metamorphic	—	—
Volcanic	—	—
Vein	—	—
Lignite	—	—
Black shale	—	—
Collapse breccia pipe	—	—
Phosphorite	—	—
Other	—	—

Source: Deposit types from OECD Nuclear Energy Agency and International Atomic Energy Agency (2000). Economic significance from McKay and Mieizitis (2001).

South Australian palaeochannel-hosted uranium deposits

Although almost every known palaeochannel-hosted uranium deposit has its own distinctive characteristics, roll-front mineralisation models have proven to have universal application (Harshman and Adams 1981). The key criteria of these models include uranium-rich source rocks, oxidising groundwater and a suitably porous and reduced sediment host. Large areas of the Curnamona Province and Gawler Craton satisfy these criteria. Evidence for the successful combination of these is demonstrated by numerous uranium prospects associated with Cainozoic palaeochannels of South Australia (Fig. 1). Important examples include deposits at Beverley, Four Mile, Honeymoon and Goulds Dam within the Curnamona Province, and at the Warrior and Yarranna prospects of the Gawler Craton. All these uranium occurrences are in Eocene to Miocene sediments and

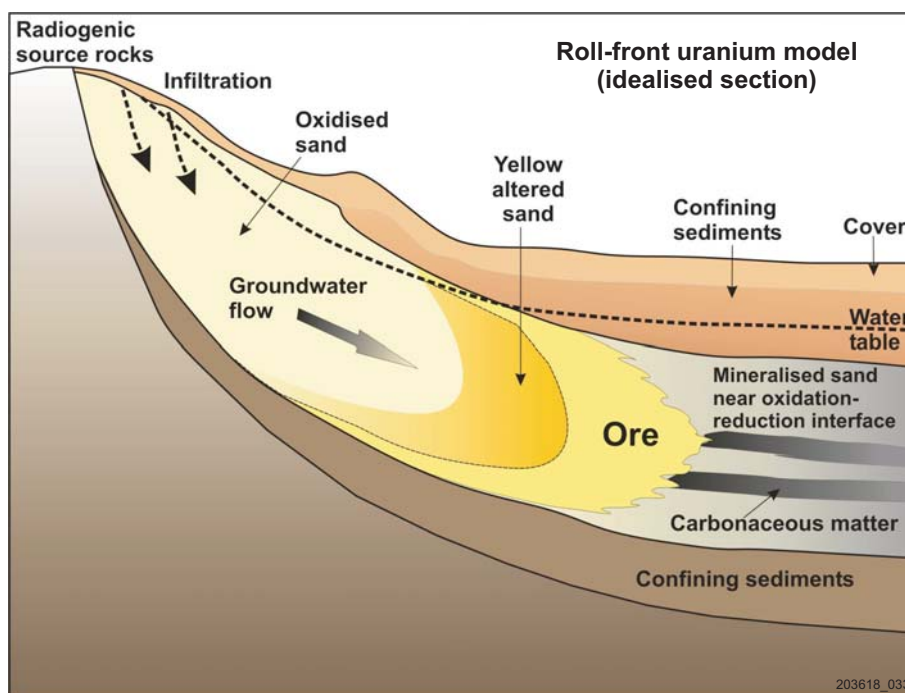


Figure 2 Generalised conceptual model of uranium roll-front deposits, modified from published sources (e.g. Devoto 1978).

characterised by high organic content that is related to widespread colonisation by land plants during this time (Alley and Lindsay 1995).

The necessity of a proximal basement source of uranium to form a sandstone-hosted or unconformity-related deposit is a point of current debate, with some research indicating that enrichment of uranium from leaching of weakly uraniumiferous sands within the sedimentary environment is sufficient. Nevertheless, the presence of spatially related uranium-rich granites (such as the Mesoproterozoic Hiltaba Suite in the Gawler Craton and its broad equivalents) is a desirable component of the mineral system. Within the Curnamona and Gawler regions, uranium contents of basement rocks are in the range 10–100 ppm, well above the crustal average of 2.8 ppm uranium (Table 2). A spatial relationship is evident between areas of high uranium in basement and uranium mineralisation

within the surrounding sediments, for example, Beverley and Four Mile deposits are in close proximity to uranium-enriched granites and gneisses of the Mount Painter Inlier in the northern Curnamona Province. Palaeochannels overlying the Gawler Craton are also sourced from uraniumiferous basement rocks, although the more westerly and northerly channels also have sediment contribution from the Musgrave Province where the uranium content in basement rocks is largely unknown (Fig. 1). Deeply weathered basement rocks were incised during Paleocene–Eocene times and the sediments in these palaeodrainage networks now form several significant uranium occurrences. The presence of key ingredients for uranium deposit formation, together with identified resources, make South Australia highly prospective for palaeochannel-hosted uranium deposits, particularly sandstone (roll-front) styles. Surficial deposits are also highly

prospective and have to date attracted little attention as an exploration target.

Palaeochannel-hosted uranium deposits in South Australia have the following characteristics (Hou, Fabris and Keeling 2005):

- Palaeochannels drained deeply weathered high-uranium source rocks.
- Mostly occur in Eocene and Miocene sediments (a likely result of changing palaeoclimatic conditions during the Cainozoic with associated weathering and erosion of granitic/metamorphic provenances and subsequent supply of oxygenated solutions under arid to semi-arid climatic regimes).
- Host rocks were deposited, generally, in fluvial and lacustrine environments in settings including channel, lagoon and marginal basin.
- Host rocks have good regional groundwater transmissivity.
- Host-rock sandstones are bounded by clay units, and are generally buried by a minimum 80 m thickness of overlying sediment.
- Provenance of sediment was commonly granitic terranes that are at least in part uraniumiferous.
- Fossil carbonised plant matter or humic matter is commonly present.
- Uranium concentrations are controlled by sedimentary and diagenetic features, but may be related indirectly to tectonic structures and basement composition that potentially modify sedimentation, groundwater flow or groundwater composition.
- Uranium is precipitated along a redox boundary at the lateral margins of the palaeochannel.
- The mineralising solutions were low-temperature groundwater.
- The ore minerals are epigenetically derived from long-term weathering processes in the Curnamona and Gawler regions, although diagenetic processes also have significance in controlling mobilisation and deposition.
- Mineralisation takes place in those palaeochannels generally incised in low-relief cratonic regions (Gawler and Curnamona) with low-angle basinward discharge dips, which allows for deposit preservation (e.g. Eucla Basin and Callabonna Sub-basin).
- Neotectonic activity has been significant in some regions (e.g.

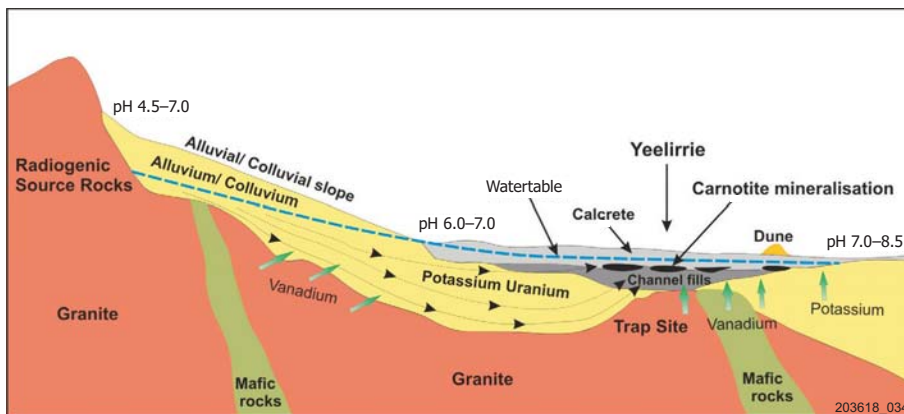


Figure 3 Idealised model of valley-fill calcrete uranium mineralisation: example from the Yeelirrie deposits of Western Australia (after Mann and Deutscher 1978).

Table 2 Uranium values in igneous and metamorphic rocks in the Curnamona Province and Gawler Craton

Rock type (unit)	Region	Number of samples	Average (ppm)	Median (ppm)	Maximum (ppm)
Gneiss	Curnamona	489	37	4	2400
	Gawler	559	5	4	100
Schist	Curnamona	269	487	130	4900
	Gawler	173	7	6	32
Migmatite	Curnamona	53	70	30	780
Volcanic	Curnamona	18	11	8	27
	Gawler	389	8	5	290
Granite	Curnamona	592	28	6	327
	Gawler	660	10	4	550
Hiltaba Suite	Gawler	236	6	4	100
Roxby Downs Granite	Gawler	—	20	—	—
Olympic Dam ore	Gawler	—	600	—	—

Note: Averages may be skewed by highly anomalous samples, particularly where the number of analyses is small. The data is a summary of samples where uranium values were determined and may not be representative of general background values.

Beverley) and may have resulted in channelling fluids along faults and/or redistribution of uranium.

Exploration techniques

Exploration for palaeochannel-hosted uranium deposits has traditionally focused on defining palaeochannels and changes in a channel's course resulting in a reduction of channel flow, accumulation of organic matter (reducing material) and build up of medium- to coarse-grained sediments (point bar and overbank deposits). Other targets include channel confluences that provide an opportunity for mixing fluids of different oxidation potential (Eh). Techniques have been developed to define channel morphology even where buried by over 100 m of exotic cover sediment (e.g. airborne electromagnetic (AEM), remote sensing; Hou and Mauger 2005; Hou, Frakes and Alley 2001; Hou et al. 2003).

Remote sensing imagery

Digital elevation model (DEM). DEMs are useful to provide indirect associations related to links between modern and ancient (e.g. Palaeogene) landscapes, although they may not directly show the distribution of palaeochannel landforms. With increasing resolution, the detail of interpretation will increase.

Landsat Thematic Mapper (TM). Processed Landsat TM satellite imagery is useful for regolith-landform mapping, particularly when draped over a DEM to enhance terrane visualisation (e.g. as used to map the Tallaringa Palaeodrainage system). These maps can be used to identify palaeochannels where the palaeochannel influences surface features and regolith materials (e.g. vegetation association, arrangement of playa lakes, alluvial terraces, silicification).

ASTER and hyperspectral remote sensing. Compared to the Landsat imagery (7 bands), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and hyperspectral remote sensing contain more spectral bands (14 and >100 bands, respectively) and can potentially distinguish most surficial features related to palaeochannels.

NOAA-AVHRR. The detector and orbital configuration of NOAA-AVHRR (National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer) and ASTER night-time satellites provide thermal data

that is potentially useful for detecting temperature variations in subsurface sediments related to the elevated moisture content of the channel. Thermal data can therefore be used as a quick and inexpensive method for mapping palaeochannels, particularly when used in conjunction with other data sets and preferably with some drillhole or geological control.

Geophysical methods

Magnetic. Palaeochannel magnetic (either positive or negative) anomalies may be defined if high-resolution surveys are used and if there are sufficient magnetic minerals in the channels or measurable magnetic contrast between the channel sediments and bedrock. Cainozoic palaeochannels are not usually visible on regional magnetic data, as they are relatively shallow features, but careful use of detailed surveys may assist in locating channel deposits.

Gravity. Gravity anomalies in the earth's gravitational field can in some cases be used to define the thickness and extent of the fluvial sediments, and hence palaeochannels, due to the contrast in density between the sediments and fresh bedrock. For example, the density of sand and clay is ~1.8g/cc and granitic basement is 2.7 g/cc (Berkman 1995).

Radiometric. Radiometric data is not a mapping tool for buried palaeochannels, but is effective in linking physical dispersion of sediment with uranium-rich source regions, especially when overlain on DEM, Landsat, NOAA, airborne magnetic (AM) or AEM images.

Electromagnetic. Electromagnetic (AEM and transient electromagnetic (TEM)) methods measure the electrical conductivity of the ground both laterally and vertically. The data can be processed to show ground conductivity as a function of depth and can define channel sediments due to their porosity, moisture content and the conductivity of the groundwater within them. This technique has been used successfully in South Australia for palaeochannel identification, for example, Garford Palaeochannel, palaeochannel sediments near the Challenger Gold Mine and on the southern margin of the Curnamona Province. However, the technique is problematic for application in parts of the Curnamona Province due to thickness of accumulated sediment fill, the presence of thick conductive clay units, perched water and multiple-stacked meandering channel fill.

Seismic. Shallow seismic reflection and refraction imaging can be used for investigating subsurface structure (particularly in sedimentary terranes) and therefore have application for delineating palaeochannels. By integrating reflection and refraction techniques, it is possible to determine palaeochannel depths, variability of materials, and the morphologies of both shallow and deeper strata (Drummond 2002).

Ground penetrating radar (GPR). The GPR method is useful for delineating the geometry, structure and thickness of channel deposits by providing a high-resolution image of subsurface features in the form of a cross-section view. The technique is only suitable for shallow investigation (up to tens of metres in ideal conditions).

Geochemical methods

Groundwater geochemistry for uranium in solution usually gives misleading results; however multi-element data from a limited number of boreholes can be used to distinguish prospective sediments by taking into account pH, equilibrium with carbonate minerals and carbonaceous matter content (Giblin 1987).

The delineation of palaeochannel-hosted uranium by surface geochemical methods is not well established, particularly for deeply buried deposits. No successful methods have been reported in South Australia. Elsewhere, techniques that have been used with some success include gas methods (gas vapour probe (GVP), radon), soil sampling (shallow deposits) and CHIM electro-geochemical methods (Fabris et al. 2006; Luo, Taofa and Hou 2004; Luo et al. 2006).

Structural and basement geology

Basement structure and composition may be important in controlling channel morphology and, ultimately, the location of uranium mineralisation. Holbrook and Schumm (1999) showed that an increase in slope along the course of a channel, commonly related to uplift, would result in increased sinuosity. The Honeymoon deposit is located at a pronounced bend in the host Yarramba Palaeovalley, where gravity and magnetic imagery indicate a fault crosscutting the channel. Here, the channel is more deeply incised into the basement at a point that corresponds to a regional-scale redox interface within the basement lithologies. The Goulds Dam deposit is also located on a crosscutting

basement fault. Activation of this fault during sedimentation may have caused the kink in the channel (as evident in AEM imagery and supported by drilling) leading to organic matter build-up and suitable conditions for precipitation of uranium.

Sedimentological analysis

Sedimentological data and interpretation, when combined with other geological and geophysical information, can be used to provide a general reconstruction of the palaeochannel architecture and history (Hou and Mauger 2005). Knowledge of the stratigraphic and geographic evolution of the area is necessary to interpret the regional depositional, environmental and palaeographic framework (Hou 2004). Sequence stratigraphic methods, supplemented by studies in palaeoclimate, mineralogy, petrology and geochemistry, have proved useful in studies on the Gawler Craton (Hou, Frakes and Alley 2001).

3D computer modelling

Where sufficient data are available, 3D visualisation models of the palaeovalley landform can provide crucial insights into the landscape evolution and controls on the dynamics of palaeorivers (Fig. 4). The palaeochannels interpreted from GIS and geophysical data sets can be viewed as 3D plume diagrams, mapped onto surfaces, or as slices, such as the palaeochannel and palaeolandscapes with exploded layers separating variously aged palaeosurfaces (Hou 2004; Hou, Alley and Gray 2004).

Location, definition and assessment of mineralisation

Many prospective palaeochannels containing oxidised and reduced sands with uranium at redox interfaces have been identified within regions of South Australia (Fig. 1). Test drilling is required to check and refine the palaeochannel interpretation (Hou 2004; Hou et al. 2003). Drillhole data needs to be continually updated to refine and improve the detail of palaeochannel mapping. In the Gawler Craton spectral logging of samples using PIMA II (Portable Infrared Mineral Analyser II) has been useful in providing a consistent independent means of identifying palaeosurfaces for input into 3D palaeochannel models (Hou and Mauger 2005). Downhole geophysical logs (e.g. gamma, electric logs, neutron) are not only essential tools for defining stratigraphic parameters used to

distinguish prospective host units, but also in the case of gamma and PFN (prompt fission neutron) tools, can be useful in estimating the grade of in situ uranium mineralisation. In combination with visual logging of cuttings, these data provide inputs for sedimentary facies analysis and reconstruction of palaeochannel architecture to model the orientation and sedimentological constraints on mineralisation.

Palaeochannel mapping

A preliminary 1:2 million scale map of palaeodrainage and Tertiary coastal barriers of South Australia was released by PIRSA in May 2007 and an associated GIS data set DVD and updated map released in June (Hou et al. 2007). The map updates Rogers (2000) and provides a context for palaeodrainage systems in the state. As such, it is most useful in the conceptual stage of exploration programs. The thematic map includes time-scaled palaeochannels, palaeocoastal barriers and strandlines, together with known mineral occurrences including uranium and heavy minerals. When used in combination with other spatial layers, especially geology and geophysics, the 'essential ingredients' for a particular uranium mineralisation model can be compared and evaluated in order to identify areas with potential to host uranium. In most cases, additional techniques will be required to define the detail of the palaeodrainage.

For the Gawler Craton and Musgrave Province, subtle palaeodrainage-landform features apparent from detailed elevation data have been combined with other data sets in GIS to identify palaeodrainage

patterns. The widespread cover of younger sediment in the Curnamona Province places greater emphasis on techniques that map the older buried channels. Much of the interpretation for these covered areas is therefore more speculative and is based on the integration of drillhole samples, interpretation of remotely sensed data (particularly night-time thermal imagery), geophysical data (particularly AEM and TEM) and knowledge of continental sedimentation and sedimentary history of South Australia.

Discussion and conclusion

Palaeochannel-hosted uranium models are important for exploration as they can be used to integrate a wide variety of potentially significant geological factors leading to the formation of deposits. Improved understanding of geological controls and landscape history can assist with target definition and choice of technique when mapping palaeochannel distribution. Regional exploration for sedimentary uranium deposits can be based initially on empirical data gained from known deposits. Models will evolve as additional data is gathered during exploration and from ongoing sedimentological studies. Exploration should begin with the delineation of palaeodrainage by the examination of a combination of inexpensive surface and remotely sensed data using GIS (e.g. available geological mapping, DEMs, airborne radiometric, Landsat TM, NOAA, ASTER, night-time thermal images). The model can then be

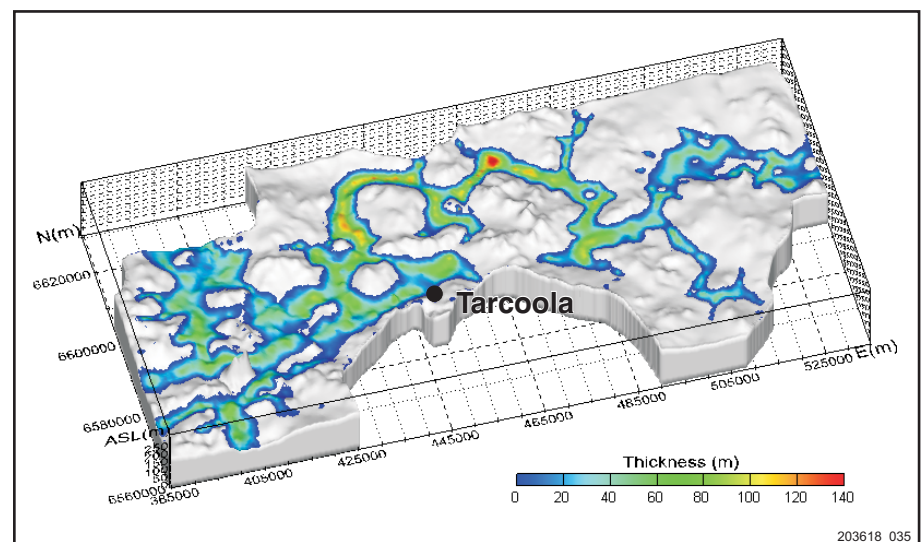


Figure 4 Kingoonya Palaeochannel: 3D model of distribution and thickness of Cainozoic sediments using available drillhole data (from Hou 2004).

progressed using geophysical techniques (e.g. AEM and/or TEM) and drilling. The ultimate aim is to construct 3D geological representations in which the sedimentary facies and depositional patterns can be mapped; alteration and facies trends traced; structural features identified; and finally the mineralising system outlined and evaluated.

Acknowledgements

This is a revised version of a paper presented at the 2006 Australian Earth Science Convention held on 1–6 July 2006 in Melbourne, Australia. This paper has benefited from various discussions with industry personnel (e.g. Heathgate Resources Pty Ltd, Red Metal Limited, Southern Cross Resources) and international researchers (e.g. United States, Canada, Russia, India, China) through IGCP 514. We are grateful for the advice of colleagues, especially Roger Fidler, Mark McGeough, Stephen Petrie, Steve Hore, Vicki Stamoulis, Alan Mauger, Domenic Calandro and Laszlo Katona, on various aspects of uranium geochemistry and applying remote sensing, geochemical, geophysical and GIS techniques. A preliminary version of the paper was improved following helpful review comments from Andrea Marsland-Smith, Uranium Equities Limited.

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