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Uranium Content of Igneous Rocks of Australia 1:5 000 000 Maps:

Explanatory notes and discussion

Anthony Schofield

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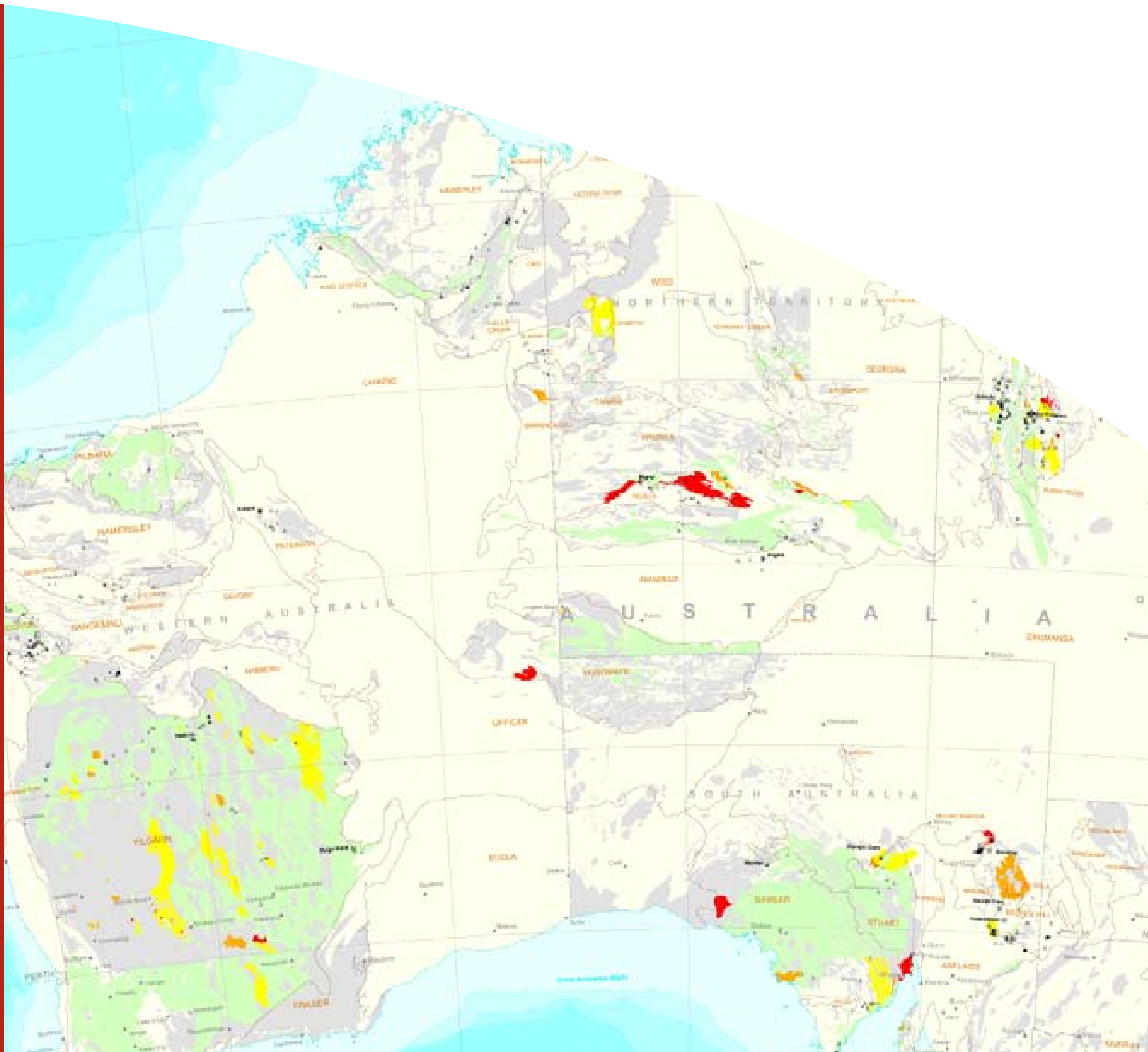

Uranium content of igneous rocks of Australia 1:5 000 000 maps – Explanatory notes and discussion

GEOSCIENCE AUSTRALIA
RECORD 2009/17

by

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Executive Summary

Magmatic-related U resources are globally significant. Nevertheless, this class of U mineralisation is poorly represented amongst Australia's total known resources. This is despite the presence of numerous U-rich magmatic events distributed across a large portion of the country, and across a vast span of geological time. To assess the potential for magmatic-related U mineral systems in Australia, three maps have been produced showing the U contents of Australian igneous rocks. Geological datasets incorporating both solid and surface geology, as well as geochemical data, have been compiled from a diverse range of open-file sources. This Record is intended to provide background information relating to these data sources and methodologies used in the production of the maps.

The maps illustrate the large spatial extent of U-rich igneous rocks in Australia, with occurrences in all jurisdictions where U exploration is currently permitted. The maps also permit ready recognition of particularly U-enriched rocks on a pluton- or wider-scale. Identification of these areas has application to exploration for both magmatic-related U systems, and certain basin-related U systems, where U-rich igneous rocks may form part of the metal source.

Analysis of the compiled geochemical data reveal that high U content is most commonly associated with evidence of extensive fractional crystallisation. Fluorine contents, bulk rock composition, melt temperature, and temporal setting are also important. This preliminary interpretation demonstrates that an applied understanding of well-known igneous processes is able to account for the observed U content in uraniferous igneous rocks. Recommendations are given for future avenues of investigation into the prospectivity of Australian igneous rocks for magmatic-related U mineral systems, based on an understanding of the geochemical behaviour of U in igneous processes.

Introduction

Igneous activity and processes are fundamental to the distribution of U throughout the earth. Uranium behaves as a highly incompatible element during processes of partial melting and magmatic evolution, which has led to the enrichment of U in the upper continental crust over geological time. Average U abundances reflect this. Typical mantle-derived magmas (mid-ocean ridge basalts - MORB) contain average U abundances of less than 0.5 ppm (Sun and McDonough, 1989). By comparison, the upper crust has an average content of 2.5 ppm (Plant et al., 1999), and felsic igneous rocks contain around 4 ppm (Rogers and Adams, 1969). Thus, crustal anatexis can yield magmas enriched in U. By combining favourable magmatic processes and physico-chemical conditions, sufficient concentrations may be achieved to result in economic mineralisation.

Uranium-rich igneous rocks are recognised as an important source of metals in U mineral systems. The relationship is evidenced by the broad spatial correlation between known U deposits in Australia and igneous rocks containing high abundances of U (Lambert et al., 2005). Magmatic-related U mineralisation may be orthomagmatic in origin, forming via favourable igneous processes, or may result from the exsolution of U-rich hydrothermal fluids from magmas with particular properties. Notable examples of magmatic-related U mineralisation include the Rössing deposit in Namibia (Berning et al., 1976), the Kvanefjeld deposit in Greenland (Larsen and Sørensen, 1987) and the Streltsovka Caldera in Russia (Chabiron et al., 2003). Despite the global importance of this family of deposits, magmatic-related U mineralisation constitutes only a very small proportion of Australia's total known U resources (McKay and Miezitis, 2001), with examples including the intrusive-related Crocker Well and Mount Victoria deposits in South Australia, and possibly the volcanic-hosted Maureen and Ben Lomond deposits in Queensland (McKay and Miezitis, 2001), although there is some debate as to whether the latter two are true magmatic deposits (Wall, 2006).

As part of the Onshore Energy Security Program, Geoscience Australia is investigating Australia's potential for undiscovered U resources. By applying the mineral systems approach (Wyborn et al., 1994; Jaques et al., 2002), a new scheme of U mineral systems has been developed (Skirrow et al., 2009). Magmatic-related U systems constitute one end-member in the scheme, which also includes basin-related and metamorphic-related U systems. Within this framework, it is recognised that igneous rocks may also contribute directly or indirectly to basin-related U mineral systems as a metal source. Thus, mapping of the distribution of U in igneous rocks has the potential to highlight prospective regions for U mineralisation at a macro-scale.

This report accompanies a series of three maps showing the U content of Australian igneous rocks (Schofield, 2009a; 2009b; 2009c). The maps incorporate geochemical and surface and solid geology datasets. Maps 1 and 2 incorporate geochemical data and surface geology datasets, while Map 3 combines geochemistry with solid geology. Together, these maps may be used to examine the spatial relationship between known U mineralisation and U-enriched igneous rocks. Using the mapped data, gross trends in igneous U content will be described. The origin of the enrichment of U in Australian igneous rocks will also be discussed.

Data compilation and interpretive methods

DATASETS

In order to investigate the spatial distribution of U-enriched igneous rocks, and their spatial relationship to known U mineralisation, disparate geochemical and geological datasets (both surface and solid geology) were drawn together from a wide range of sources. This section will briefly discuss data sources and coverage. Appendix gives a comprehensive listing of all datasets used.

Geochemical data

Geoscience Australia's OZCHEM database is the primary geochemical dataset utilised for this investigation. OZCHEM is a comprehensive nation-wide geochemical dataset, and contains inorganic geochemical analyses from all rock types. OZCHEM data were supplemented with additional open file data provided by geoscience agencies in New South Wales, Queensland, South Australia, and the Northern Territory.

Raw data from all sources were filtered to eliminate non-igneous lithologies, and compiled into a single, uniformly attributed dataset. Analytical quality and precision is highly variable across the data compiled. Where possible, U values were eliminated in cases where they were determined by analytical techniques deemed to be unreliable. Samples with a high likelihood of having disrupted U contents (i.e., by non-magmatic enrichment or depletion) were identified on the basis of sample descriptions, loss on ignition (LOI) values, and Th/U ratios. Only samples with a sum of major elements of 100±1.0% were considered when calculating indices such as the aluminium saturation index (ASI; calculated as the molecular ratio of $Al_2O_3/Na_2O+K_2O+(CaO-3.3*P_2O_5)$) and zircon saturation temperature (T_{Zr}), calculated according to Watson and Harrison (1983).

Although the utmost care has been taken to select only the most reliable analyses, it is not possible to guarantee that all U values used reflect true magmatic compositions, or that the dataset is devoid of unreliable analyses. In particular, datasets derived from analyses undertaken by mineral exploration companies may be heavily biased towards mineralisation, and these have been eliminated as far as possible.

Samples were categorised into four broad igneous rock types based on sample description: mafic (includes ultramafic compositions), intermediate, felsic and alkaline. Based on the recognition of spurious sample descriptions entered into the original datasets, the geochemical data were additionally divided into broad igneous rock types on the basis of silica content (calculated anhydrous), with ultramafic samples containing <45% SiO_2, mafic samples with 45 – 52%, intermediate rocks with 52 – 63%, and felsic rocks with >63%. Classification based on silica content is the preferred method used in this study, as it ensures a consistent standard across all samples, and is not dependant on what is in some cases an ambiguous or erroneous description. Both intrusive and extrusive lithologies have been used.

Geological datasets

Both surface and solid geology datasets were used in the production of the maps accompanying this report. Maps 1 and 2 are based on surface geology, which is extracted from Geoscience Australia's recently released 1:1,000,000 national surface geology coverage. This dataset is seamless across Australia, and has the advantage of having a uniform attribute schema. This latter feature has allowed for igneous lithologies to be readily extracted. Map 3 utilises solid geology coverages (data sources listed in Appendix). No seamless and consistently attributed solid geology coverage exists for the entire Australian continent. Therefore, various State and Territory solid geology datasets have been compiled. Care has been taken to select the best solid geology coverages available (Fig. 1), and as a result scale, accuracy and representativeness of individual coverages may vary.

Igneous units were identified and extracted largely based on lithological descriptions. In many instances, igneous, metamorphic and sedimentary rocks have been grouped together into a single geological polygon. Where this is the case, the unit has been classified as either having the igneous component as the primary or subordinate lithology. For the purposes of generating maps and interpretation, only polygons with igneous rocks as the primary lithology were used. While in most cases the dominant lithology is listed as an attribute within the original dataset, this is not universally so, and the primacy of igneous lithologies within a polygon was established on the basis of its order of listing in the description. Even so, some 'igneous units' still contain a sedimentary or metamorphic component, albeit a subordinate one. Both surface and solid geology datasets were then classified into igneous compositions.

Given the heterogeneous attribute schema of the compiled solid geology coverages, all datasets were reattributed with a new schema. This new attribute scheme contains information on igneous rock category (e.g., felsic, mafic), data source, minimum age, maximum age, unit name, and a description of each individual unit, as listed in the parent dataset. This allows all datasets to be merged together in a GIS environment, and ensures internal consistency is maintained.

Igneous classifications (e.g., supersuite) used in this report are derived from the usage within the compiled geological and geochemical datasets. The relevant literature addressing igneous classification has not been cited in this report. Readers are instead referred to the datasets listed in Appendix for additional information.

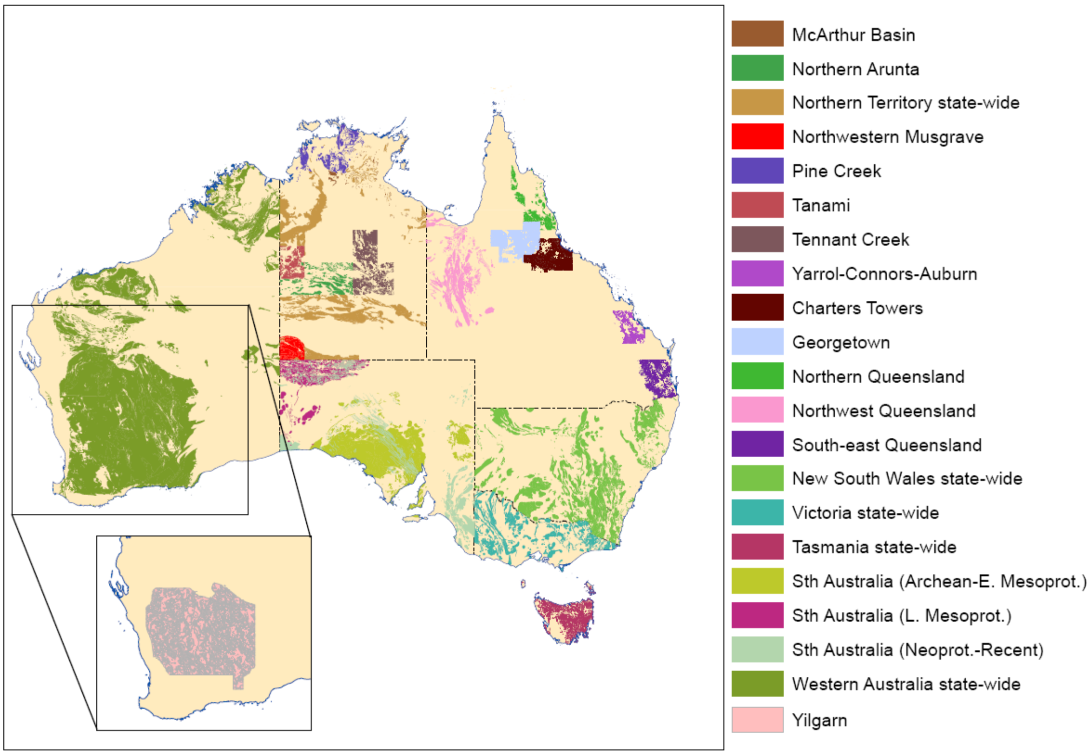

Figure 1: *Distribution of solid geology datasets utilised in this study. Data sources are detailed in Appendix.*

DATA INTERPRETATION METHODS

Two different techniques were employed in portraying the spatial distribution of U in igneous rocks: point-based and polygon-based.

Point-based interpretation

Preliminary data interpretation was undertaken based on an analysis of the compiled geochemical points as individual entities. This is the approach illustrated in Map 1. While this technique allows for rapid identification of high-U igneous samples, it is not adequate to permit more detailed interpretations related to geodynamic processes, or to reveal gross enrichment trends between igneous units. For this, additional approaches are required.

Polygon-based interpretation

Maps 2 (showing surface geology) and 3 (showing solid geology) use a polygon-based approach, similar to the technique employed by Budd (2007) for assessing the radiogenic heat production of granites. Igneous polygons were plotted together with the geochemical sample points described above using ArcGIS. Each polygon was then attributed with the average U value (in ppm) of the geochemical sample points contained within the polygon. Only sample points of the same igneous category as the intersecting polygon were considered in the averaging process (e.g., felsic samples were not considered in mafic geological units). This helps to prevent many unrepresentative samples of differing igneous category to the host polygon (as represented by localised differentiates, dykes, or other small-scale igneous features) from providing a false representation of the unit's average U content (although this does not entirely eliminate all unrepresentative samples).

This polygon-based approach allows large-scale trends in igneous rock geochemistry to be observed, and regions of anomalous U content to be delineated at a continental scale. A further advantage is that igneous U content can be assessed on the pluton-scale or greater, depending on polygon resolution. As a drawback to this method, polygon distribution may not always satisfactorily represent the true extent of igneous units, either at the surface or in the subsurface. This may result in geochemical samples occurring outside of any polygon, and therefore not considered in the averaging process, or in samples being assigned to incorrect geological units. Another disadvantage of this technique lies in the homogenising effect of averaging U in individual igneous units, which can obscure natural internal variability.

Spatial distribution of igneous uranium and general enrichment patterns

Most major Australian geological regions contain igneous rocks with U contents exceeding typical values found in granites globally, although the degree of enrichment varies between provinces. This section will describe the distribution of observed high U contents in igneous rocks in each State and the Northern Territory, as revealed in the compiled geochemical data.

WESTERN AUSTRALIA

High-U igneous rocks occur in both of the Archean terranes of Western Australia. The Pilbara Craton hosts a small number of occurrences of igneous rocks with elevated U, occurring in the Yule and Mount Edgar Granitoid Complexes. The Yilgarn Craton contains widespread U-rich igneous rocks, with individual analyses containing in excess of 20 ppm U. High-U samples correlate closely with the distribution of crustally-derived granites (Fig 2; low-Ca group of Champion and Sheraton, 1997). In contrast, the high-Ca group (mafic to intermediate source, Champion and Sheraton, 1997) contains U abundances more in keeping with typical values for granites.

Elsewhere in Western Australia, the Proterozoic Paterson Province contains clusterings of geochemical analyses with high U in the Neoproterozoic Mount Crofton Granite and the Deserts Revenge Syenogranite. Overall sample density is low in the Paterson Province, preventing meaningful spatial interpretation. The western Musgrave province also contains a small number of samples containing elevated U contents. This is additionally significant considering the overwhelmingly low-U nature typical of the rest of the Musgraves. Other uraniferous samples in the Musgrave province occur in granitic basement to the Bentley Supergroup.

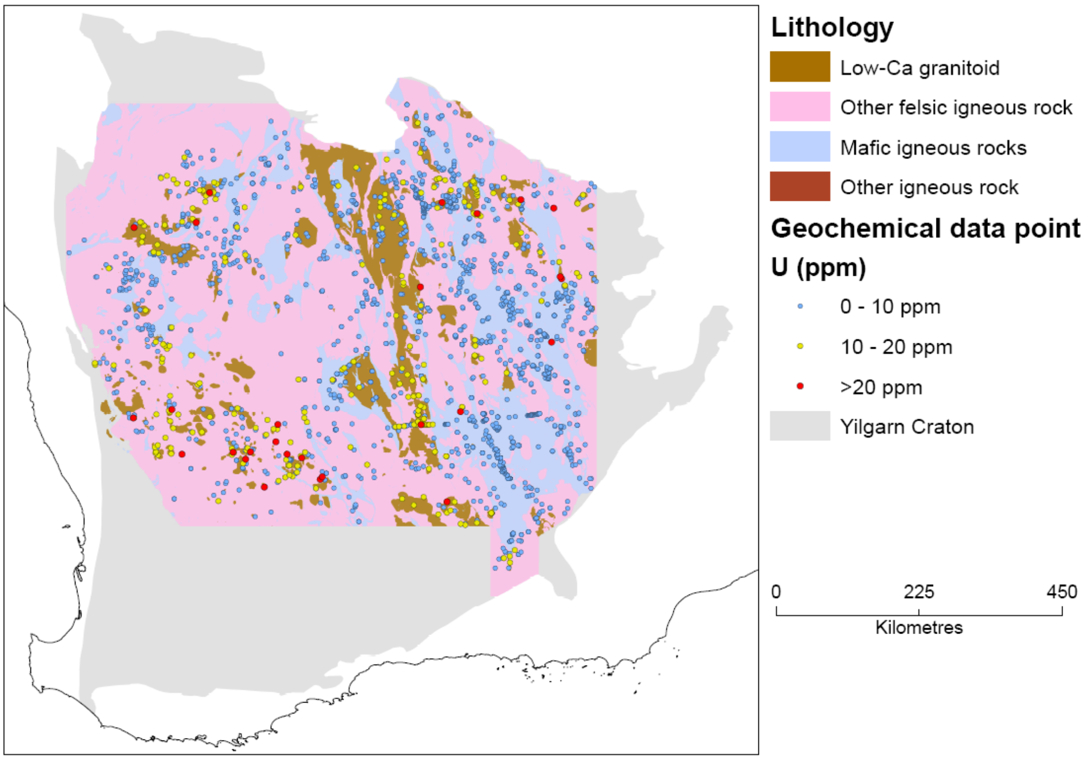

Figure 2: *Distribution of low-Ca granitoids and geochemical sample points in the Yilgarn Craton. Distribution of igneous rock categories is from Cassidy et al. (2002).*

NORTHERN TERRITORY

The main geological provinces hosting U-rich igneous rocks in the Northern Territory are the Arunta and Pine Creek regions (Fig. 3). The Pine Creek region, a known U province, contains widespread felsic igneous rocks with high U contents. In the western half of the province, most high-U samples occur in the Paleoproterozoic Cullen Supersuite. The Neoarchean Rum Jungle Complex also contains significant U enrichments. The Paleoproterozoic David Suite possesses high concentrations of U in places, and several igneous rock samples in the central Pine Creek region and the Alligator Rivers Uranium Field have analyses with U content exceeding 20 ppm.

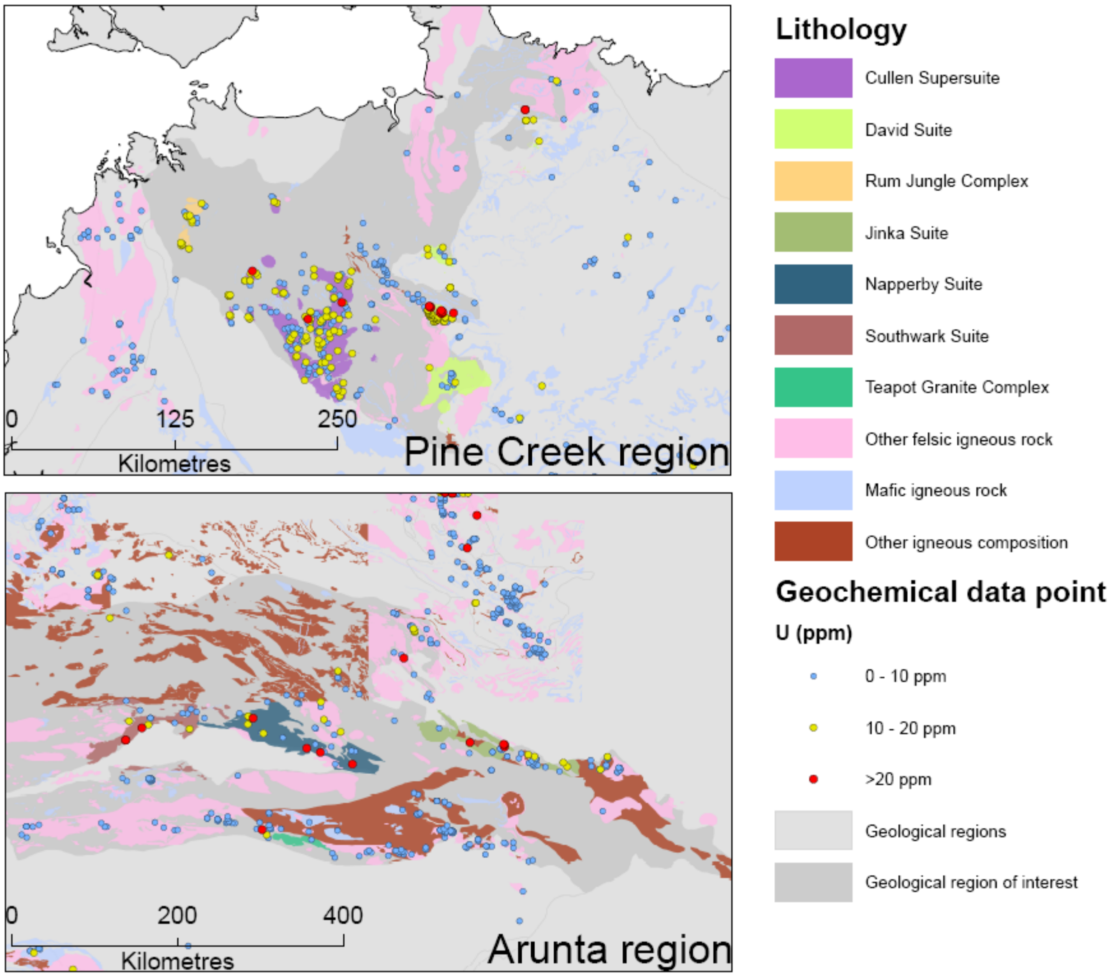

Figure 3: *Key geological regions in the Northern Territory exhibiting high-U igneous rocks. Igneous unit name and rock classification is taken from the solid geology igneous rock distribution shown in Map 3 (Schofield, 2009c).*

The Arunta region is host to several bodies of uranium-rich igneous rocks, with individual samples containing in excess of 50 ppm U. Many of the most enriched samples occur on the northern margin of the Ngalia Basin. The Southwark, Napperby and Jinka Suites are of particular interest. These suites have already been identified by Budd et al. (2001) as having potential for Cu, Au, Ta, Mo and W mineralisation. The Teapot Granite Complex in the southern Arunta region also has moderate U enrichments, and is considered to have moderate Cu-Au potential (Budd et al., 2001). Other igneous rocks of felsic composition show enrichment in U across the Arunta region, although these are largely isolated occurrences (Fig. 3). The overall low sample density around these high-U occurrences indicates that this is a region for future investigation, and possibly represents a region of previously unrecognised potential.

Elsewhere in the Northern Territory, the Tennant Creek region hosts numerous high-U igneous rocks. Most samples containing appreciable U (>20 ppm) are of exotic compositions (lamprophyre). Aside from the lamprophyric bodies, the Warrego Granite of the highly fractionated Paleoproterozoic Devils Suite is noteworthy. Data from the Murphy Inlier also indicate igneous rocks with anomalous U, coinciding with abundant U mineral occurrences.

QUEENSLAND

Two key provinces of U-enriched igneous rocks exist in Queensland: the Mount Isa and Georgetown-Cairns-Charters Towers regions (Fig. 4). Emplacement of high-U granitoids in these regions was not contemporaneous, with Carboniferous-Permian magmatism in the Georgetown-Cairns-Charters Towers region, and Paleo- to Mesoproterozoic igneous activity in the Mount Isa area.

In the Mount Isa region, numerous samples of the Paleoproterozoic Sybella Suite in the Western Fold Belt have U contents exceeding 20 ppm. In general, igneous rocks in the central belt of the Inlier (Kalkadoon-Leichardt) are closer to global average granitic values. Nevertheless, granitoids of the Wonga and Burstall Suites show patchy enrichment. The most concentrated occurrences of U-enriched igneous rocks occur in the Eastern Fold Belt, where the Mesoproterozoic Williams Supersuite shows overall elevated U contents. High-U igneous rocks in the Georgetown-Cairns-Charters Towers region are largely related to Carboniferous-Permian magmatism, most prominently represented by the O'Briens Creek Supersuite (Champion and Chappell, 1992). Some geochemical analyses of Proterozoic-aged rocks show mild elevation in U contents relative to typical granitic values, although these are minor compared to the younger granitoids.

Outside the Mount Isa and Georgetown-Cairns-Charters Towers regions, igneous rocks in the Coen region of far north Queensland exhibit limited U enrichment. In the southern half of the state, granitoids in the New England Fold Belt have high U, especially those of the Stanthorpe Supersuite. The peralkaline Peak Range Volcanics (Knutson, 1989) in the Bowen Basin are also noteworthy in terms of their U content, although there are few analyses. High-U igneous activity in these regions is Phanerozoic in age.

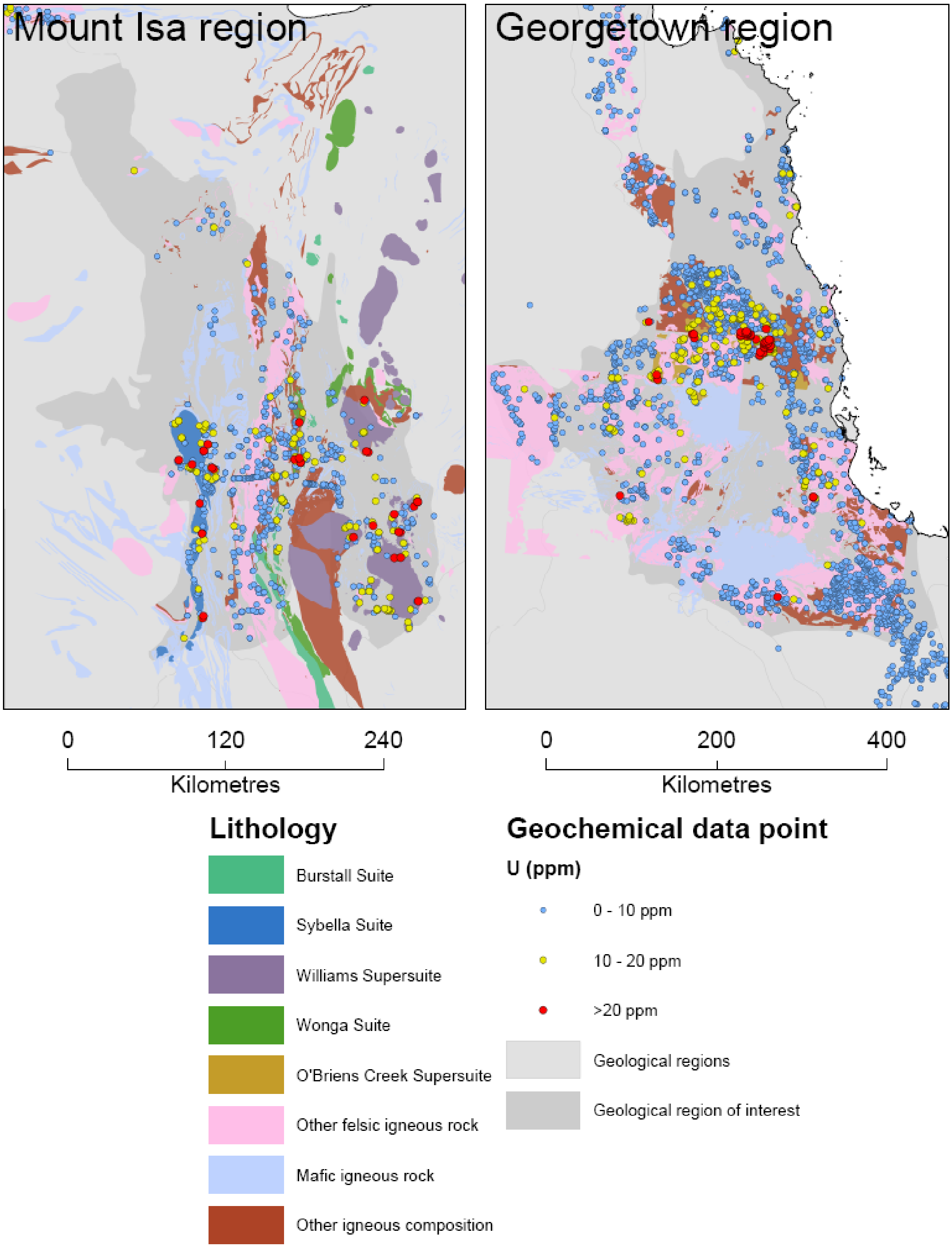

Figure 4: *Uranium content of igneous rocks in the Mount Isa and Georgetown(-Cairns-Charters Towers) regions of Queensland. Igneous unit name and rock classification is taken from the solid geology igneous rock distribution shown in Map 3 (Schofield, 2009c).*

SOUTH AUSTRALIA

South Australia contains numerous examples of uraniferous igneous rocks distributed across a large part of the state (Fig. 5). The Archean to Proterozoic Gawler Craton hosts many of these, especially in the voluminous Mesoproterozoic Hiltaba Suite. The A-type-like Roxby Downs granite, a component of the Hiltaba Suite, is associated with the giant IOCG-U Olympic Dam deposit.

The Mount Painter and Mount Babbage Inliers, situated on the northwestern margin of the Curnamona Province, have anomalously high U contents, and represent the most U-rich magmatic rocks in Australia. In particular, the Mesoproterozoic Babbage Supersuite has abundances of greater than 100 parts per million (Yerila granite). Other regions in the Curnamona Province exhibit elevated U contents, such as the highly alkaline (Ashley, 1984) Mesoproterozoic Crockers Well Granite of the Bimbowrie Suite.

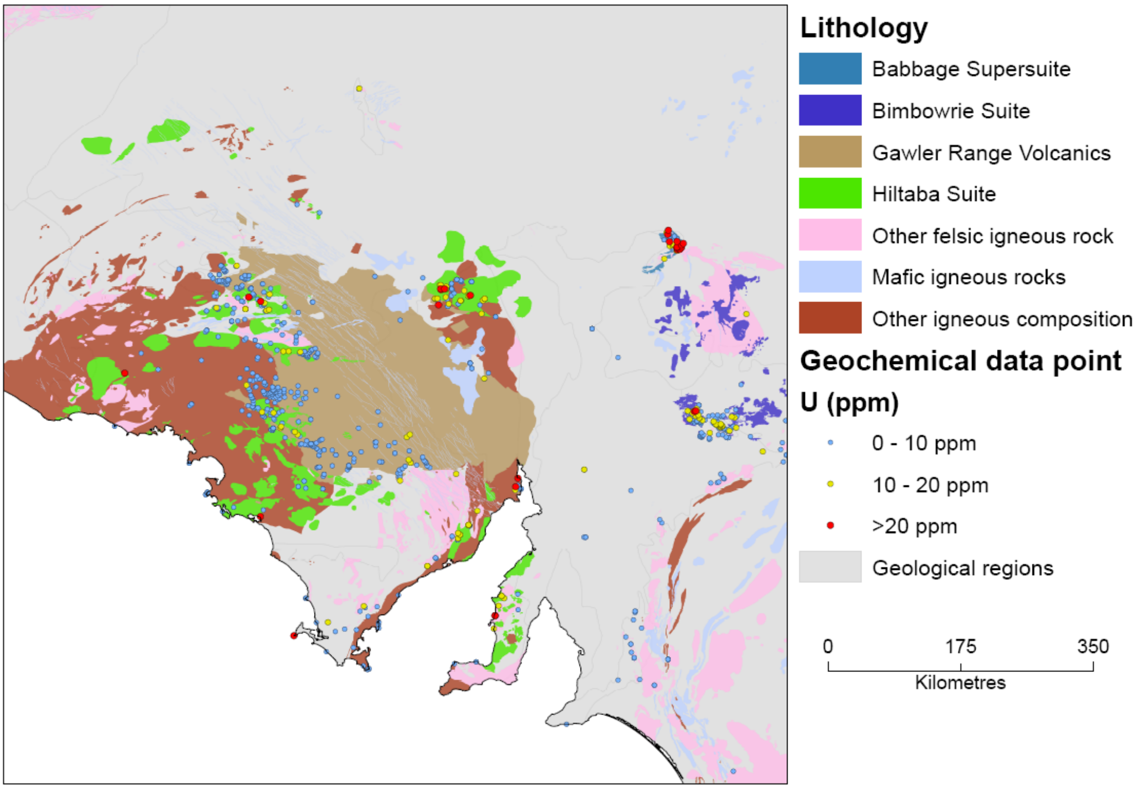

Figure 5: *Uranium content of igneous rocks in South Australia, including the Gawler Craton and Curnamona Province. Note the large spatial extent of U-rich magmatism (e.g., Hiltaba Suite). Igneous unit name and rock classification is taken from the solid geology igneous rock distribution shown in Map 3 (Schofield, 2009c).*

NEW SOUTH WALES, VICTORIA AND TASMANIA

Uranium exploration is presently prohibited in these states, and hence only a brief treatment will be provided here. Igneous rocks in the eastern states (excepting Queensland) have the lowest abundances of U in Australia. Tasmania is an exception to this general trend, with uraniferous felsic igneous rocks in the northwest and northeast of the state. Outside of Tasmania, only the New England Fold Belt near the New South Wales-Queensland border contains appreciable occurrences of U-rich igneous rocks. Scattered elevated values associated with highly evolved granitoids occur throughout the Lachlan Fold Belt in New South Wales and Victoria, although there are no identified areas with abundant occurrences of U-rich igneous rocks.

Origin of uranium enrichment in Australian igneous rocks

GEOCHEMICAL EVIDENCE

In felsic igneous rocks such as granite, elevated U abundances are most commonly associated with evidence of a high degree of fractional crystallisation. Uranium is highly incompatible in the structure of the major rock forming minerals (Bea, 1996). Therefore, little U is removed from a fractionating melt as it crystallises, allowing U to concentrate by a factor of several times its initial concentration at the time of partial melting. Most U-rich samples in this study are characterised by high SiO_2 and Rb, and low Sr and Ba, reflecting the segregation of major minerals such as feldspar from the residual melt. Variation diagrams plotting SiO_2, Sr and Rb against U clearly demonstrate a relationship between increasing U content and fractional crystallisation (Fig. 6), as has been reported by numerous studies.

Although incompatible in major minerals, U is accommodated into a wide variety of accessory mineral phases (Bea, 1996). Uranium saturation and incorporation into these minerals may occur relatively early in the crystallisation history (Farges et al., 1992). For example, uraninite saturation will occur at levels of only a few tens of ppm in peraluminous melts (Peiffert et al., 1996). Uranium solubility is enhanced by the presence of high concentrations of alkalis, Cl and F, with F playing the most important role (Peiffert et al., 1994; Peiffert et al., 1996; Mysen et al., 2004). Variation diagrams of F versus U show considerable scatter (which may reflect F mobility in some samples), with a weak positive relationship between increasing U and F (Fig. 7). Regardless of the poor correlation, the importance of F in enhancing U concentrations in the melt is evident when comparing the F concentrations in low (<20 ppm) and high (>20 ppm) U samples, with the percentage of samples containing over 1000 ppm F at 24% and 76% respectively. The overall lower F in samples which, despite having trace element abundances typical of having undergone a high degree of fractional crystallisation have low U contents, suggest that U was partitioned into various mineral phases relatively early in the crystallisation history.

Bulk rock composition plays an important part in the geochemical behaviour of U in magmatic systems (Cuney and Friedrich, 1987; Bea, 1996). When plotted against ASI, U increases with rising values, reaching a peak at weakly peraluminous compositions, before decreasing again at more highly peraluminous compositions, although high-U outliers exist at higher ASI values (Fig. 8a). This trend probably represents a transition from metaluminous to peraluminous compositions with progressive fractionation of I-types. Those samples with very high ASI values probably represent S-type compositions.

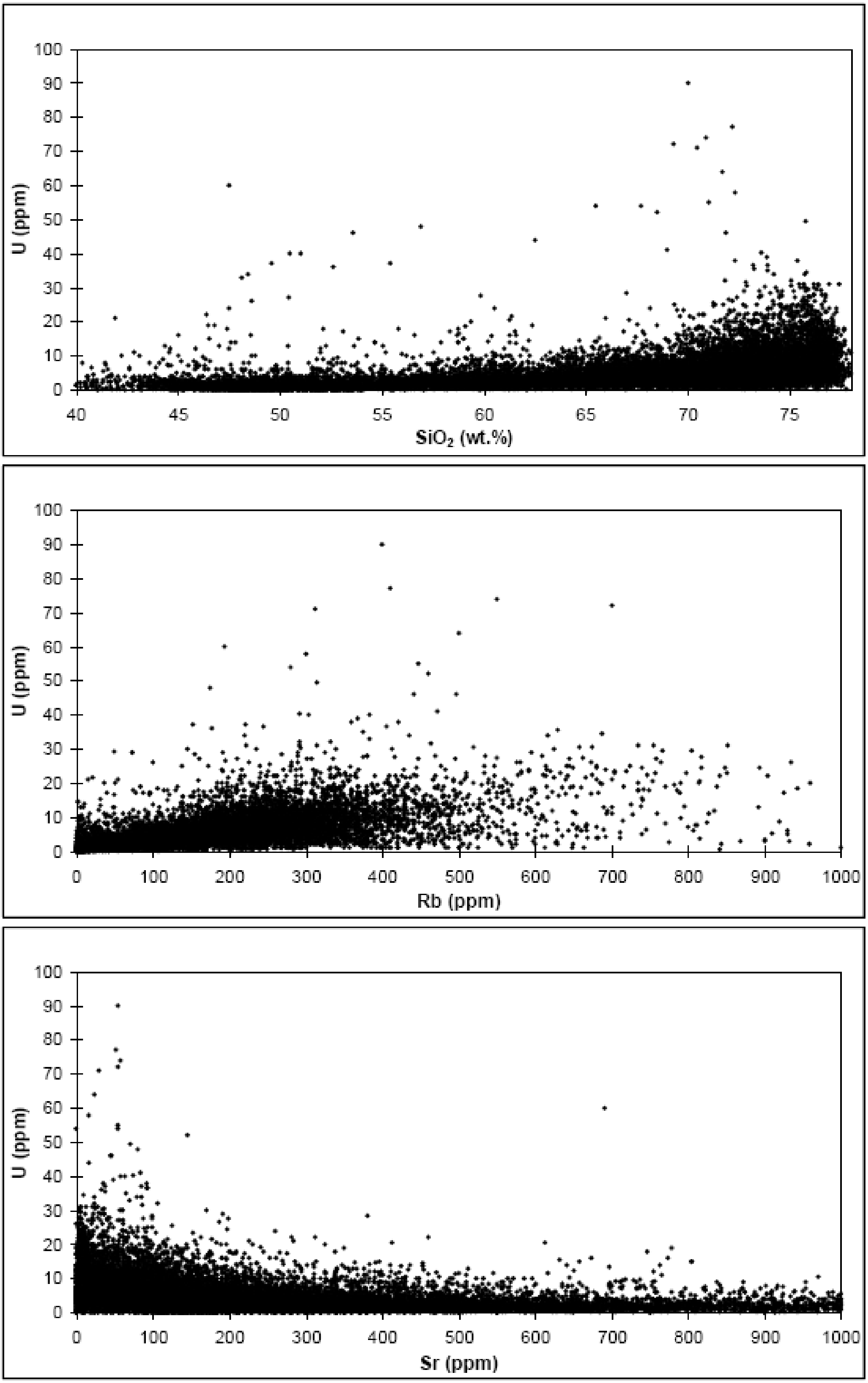

Figure 6: *Plots of SiO_2, Rb and Sr versus U for the geochemical data compiled in this investigation.*

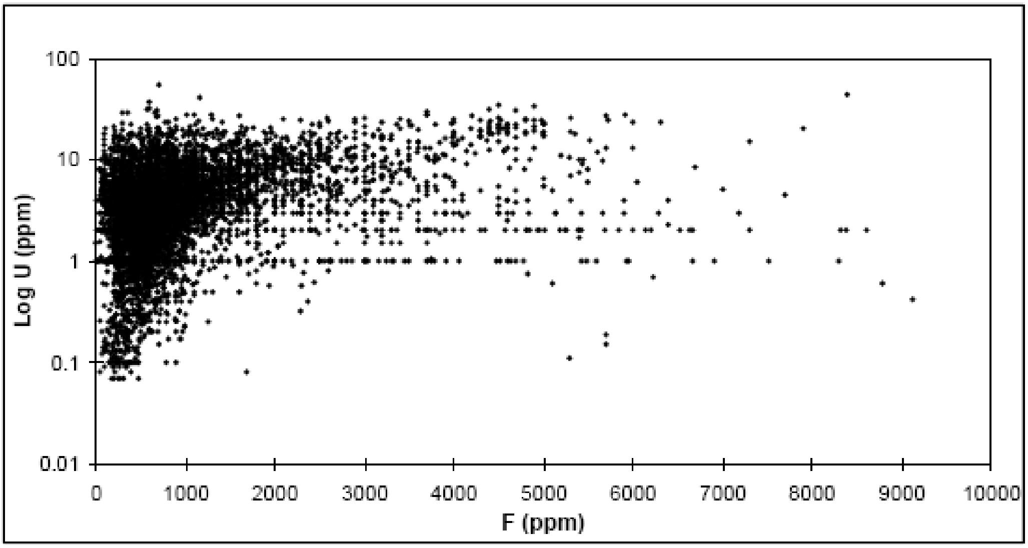

Figure 7: *Variation diagram of F versus log U for felsic igneous rocks studied in this investigation. Note that not all samples analysed for U have also been analysed for F.*

Although peralkaline felsic igneous rocks are known to be associated with extreme U enrichment (e.g., Rogers et al., 1978; Plant et al., 1999; Cuney, 2009), the data compiled in this study do not reflect this (Fig. 8b). While there is a propensity towards U contents exceeding average granite values (~4 ppm), high degrees of enrichment (>20 ppm) occur in only a small handful of samples (although the number of high U samples is higher in more exotic alkaline compositions). This is despite the highly evolved nature of many of the peralkaline rocks. Thus, a peralkaline bulk rock affinity is not necessarily diagnostic of significant U enrichment. Despite this, the global importance of this rock category with respect to U mineralisation, demands that peralkaline complexes should be considered potentially prospective, since current sampling may not capture the most U-enriched members. Another potential explanation for the seemingly small proportion of samples with very high U abundances is the overall small sample population of peralkaline felsic igneous rocks (<1% of all samples).

Approximately 1% of analysed metaluminous igneous rocks contain U contents exceeding 20 ppm. Most of these show evidence of having undergone a considerable degree of fractional crystallisation. Extremely high (>90 ppm) values in metaluminous magmas are confined to the Yerila Granite of the Mount Babbage Inlier. The Yerila Granite shows geochemical characteristics consistent with having undergone a significant degree of fractionation, although SiO_2 content is not exceedingly high (<70 wt.%). High T_{Zr} values calculated for this granite (>~900^{o}C) are probably significant in the generation of U-rich melts.

Peraluminous compositions are the most common amongst the felsic igneous rocks studied in this investigation. In general, patterns of U enrichment are similar to those of metaluminous rocks. Unlike rocks of metaluminous composition however, peraluminous igneous rocks are highly enriched not only in the Mount Painter area, but also in the Tennant Creek, Mount Isa, and Lachlan Fold Belt regions. Likewise, there are a higher proportion of samples containing over 20 ppm U in peraluminous rocks. Based on the low ASI values of most U-rich peraluminous rocks (Fig. 8a), it is likely that these represent the fractionated products of metaluminous parental magmas. Thus, the relationship between peraluminous magmas and uranium enrichment is probably related to magmatic evolution.

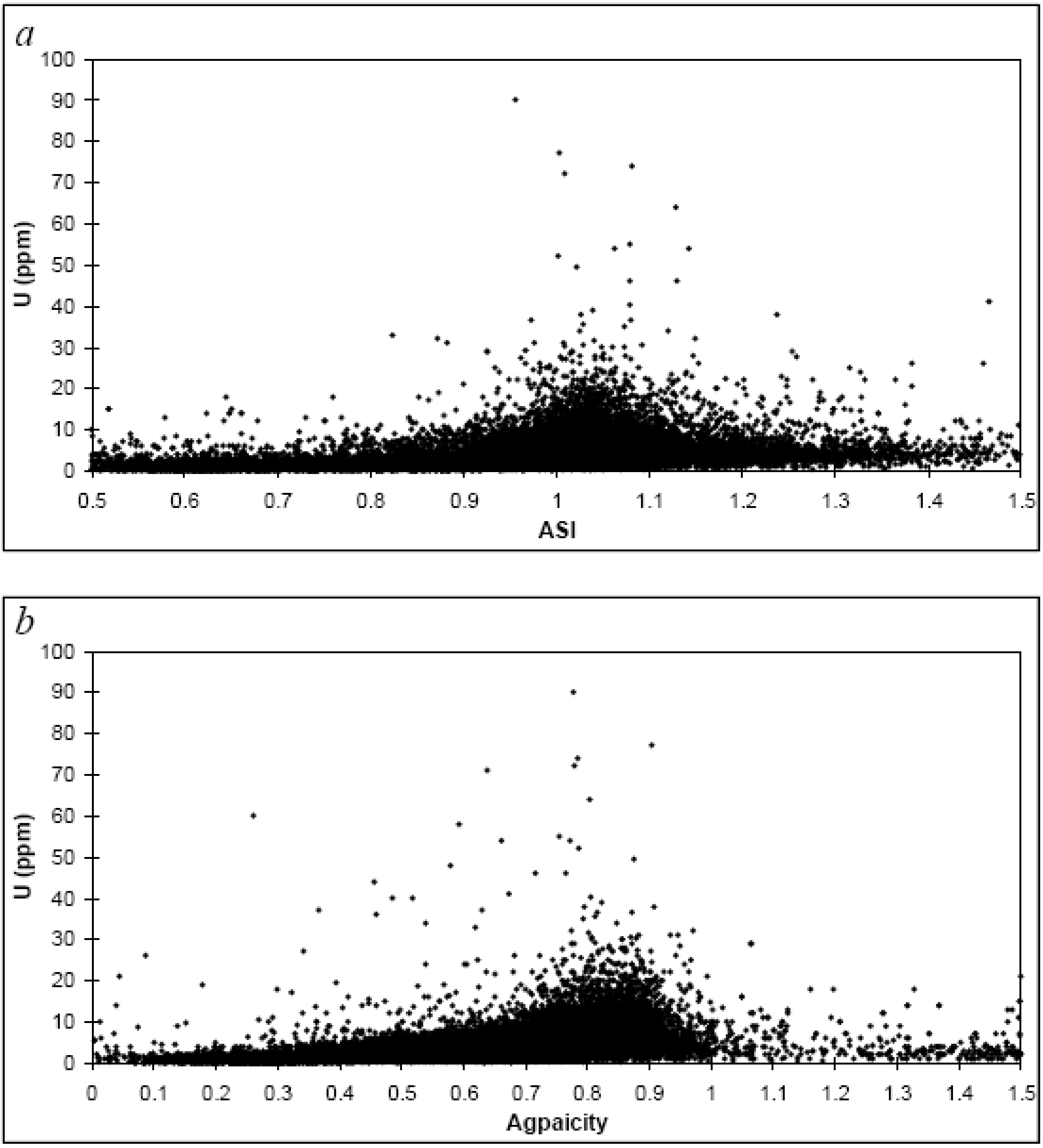

Figure 8: *Plot of ASI (a) and agpaicity (b) versus U for felsic igneous rocks studied in this investigation. The data show that U enrichment occurs across a range of bulk rock compositions. The ASI calculation is corrected for apatite, hence the metaluminous-peraluminous boundary is set at ASI = 1. Agpaicity is calculated as the molecular ratio of Na+K/Al. Peralkaline samples have an agpaitic index of >1.*

As with the most enriched metaluminous magmas, those peraluminous compositions with the highest U contents have high calculated T_{Zr} values. High melting temperature (manifested as high temperature I-type and A-type granite compositions) is considered to be a favourable 'ingredient' in the generation of a U-rich igneous rock (Plant et al., 1999). Although high T_{Zr} is not necessarily diagnostic of high U content, it appears that, at least in some cases, high T_{Zr} may be a useful discriminator between igneous units with potential for high degrees of U-enrichment and those with a lesser potential for enrichment.

The discussion above illustrates that an applied understanding of magmatic processes is able to account for many features observed in U-enriched felsic igneous rocks. However, there are also a number of samples that have geochemical characteristics consistent with having undergone favourable magmatic processes, and yet have relatively low U contents (<10 ppm). By conventional wisdom, these samples should contain higher U. Normal Th/U ratios indicate that the low U is not a product of post-magmatic depletion. One possible explanation is that these igneous rocks were generated from the melting of an unradiogenic source, thus yielding a melt with low initial U contents, or fractionated from a less radiogenic parent.

In non-felsic igneous rocks, U enrichment is typically associated with exotic, highly alkaline compositions, such as lamproites and carbonatites. These have long been recognised as containing high U. For example, lamprophyres in the Tennant Creek region of the Northern Territory contain up to nearly 50 ppm U (Duggan and Jaques, 1996). The origin of U enrichment in these rocks is readily accounted for by their unusual chemistry, which maintains extremely high U solubilities.

TEMPORAL CONSTRAINTS

Temporally, there is a bias towards U enrichment in Proterozoic igneous rocks in Australia, with Archean magmatism also of importance, particularly in the Yilgarn Craton. Phanerozoic igneous rocks are typically lower in U, although significant U-rich magmatism occurred in the Carboniferous to Permian of northern Queensland, representing some of the highest U concentrations in the country. The majority of Phanerozoic-aged igneous rocks however have U abundances generally closer to average granitic values.

The significance of Proterozoic felsic magmas in U mineralisation in Australia has previously been recognised by Lambert et al. (2005). Wyborn et al. (1998) noted that Australian Proterozoic granites are overwhelmingly dominated by Sr-depleted, Y-undepleted trace element patterns, reflecting melting at plagioclase-stable depths (<30-35 km) without the presence of residual garnet. Together with other features, granite chemistry argues in favour of an elevated thermal regime during this period. This is reflected in the current heat production of Australian felsic Proterozoic igneous rocks, which is double that of average granite (McLaren et al., 2005). A similar relationship is observed between uraniferous granites and high geothermal gradients in the Caledonian and Hercynian provinces in the British Isles (Simpson et al., 1979). These features suggest that the source of Australian Proterozoic felsic igneous rocks may have been unusually radiogenic, and highly fertile for generating U-rich melts, making Proterozoic-aged magmatism a key target for U-enriched rocks.

Summary and avenues for future work

Uranium enrichment in igneous rocks occurs in crustal regions across the entire country, and across a large span of geological time. Most U-enrichment occurs in rocks of an Archean or Proterozoic age, although Phanerozoic-aged magmatism in northern Queensland is highly significant. The geochemical data show that fractional crystallisation appears to be the dominant control on U enrichment. This is especially the case when coupled with the presence of high concentrations of solubility-enhancing agents such as Na+K, F and Cl. Other factors, such as bulk rock composition appear to play a subordinate role. High magma temperatures (as approximated by T_{Zr}) alone are unable to delineate high U igneous rocks, but high-temperature melting may be an important ingredient in the generation of some U-enriched melts.

This initial compilation has allowed the spatial extent and distribution of U-rich igneous rocks to be delineated on a continental scale, and allows for a comparison between the distribution of these and known U mineralisation. While it is clear that there is a close spatial relationship between the two, a more important question is whether there is potential for previously unrecognised magmatic-related mineralisation.

Interrogating the data with an understanding of igneous processes that may lead to a high degree of U enrichment will help to determine whether or not certain components within an igneous body have undergone the appropriate processes and evolutionary path to form either a) orthomagmatic U deposits, b) magmatic-hydrothermal U mineralisation, or c) a suitable source of U for secondary mineral systems, including basin-related U mineralisation. The latter would involve a comprehensive determination of the U-bearing mineral assemblage in order to assess the availability of U for leaching. It is suggested that the theoretical considerations presented by Skirrow et al. (2009) be employed in these assessments. By these means, prospective igneous bodies for magmatic-U mineralisation may be identified on a national scale.

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REFERENCES

Ashley, P.M., 1984. Sodic granitoids and felsic gneisses associated with uranium-thorium mineralisation, Crockers Well, South Australia. *Mineralium Deposita*, **19**, 7-18.

Bea, F., 1996. Residence of REE, Y, Th and U in granites and crustal protoliths; implications for the chemistry of crustal melts. *Journal of Petrology*, **37**, 521-552.

Berning, J., Cooke, R., Hiemstra, S.A. and Hoffman, U., 1976. The Rössing uranium deposit. South West Africa. *Economic Geology*, **71**, 351-368.

Budd, A.R., 2007. Australian radiogenic granite and sedimentary basin geothermal hot rock potential map (preliminary edition); 1:5 000 000 scale. Geoscience Australia, Canberra.

Budd, A.R., Wyborn, L.A.I. and Bastrakova, I.V., 2001. The metallogenic potential of Australian Proterozoic granites. *Geoscience Australia Record 2001/12*.

Cassidy, K.F., Champion, D.C., McNaughton, N.J., Fletcher, I.R., Whitaker, A.J., Bastrakova, I.V. and Budd, A.R., 2002. The characterisation and metallogenic significance of Archaean granitoids of the Yilgarn Craton. *Minerals and Energy Research Institute of Western Australia*, **Report 222**.

Chabiron, A., Cuney, M. and Poty, B., 2003. Possible uranium sources for the largest uranium district associated with volcanism: the Streltsovka caldera (Transbaikalia, Russia). *Mineralium Deposita*, **38**, 127-140.

Champion, D.C. and Chappell, B.W., 1992. Petrogenesis of felsic I-type granites: an example from northern Queensland. *Transactions of the Royal Society of Edinburgh*, **83**, 115-126.

Champion, D.C. and Sheraton, J.W., 1997. Geochemistry and Nd isotope systematics of Archaean granites of the Eastern Goldfields, Yilgarn Craton, Australia: implications for crustal growth processes. *Precambrian Research*, **83**, 109-132.

Cuney, M., 2009. The extreme diversity of uranium deposits. *Mineralium Deposita*, **44**, 3-9.

Cuney, M. and Friedrich, M., 1987. Physicochemical and crystal-chemical controls on accessory mineral paragenesis in granitoids: implications for uranium metallogenesis. *Bulletin de Mineralogie*, **110**, 235-247.

Duggan, M.B. and Jaques, A.L., 1996. Mineralogy and geochemistry of Proterozoic shoshonitic lamprophyres from the Tennant Creek Inlier, Northern Territory. *Australian Journal of Earth Sciences*, **43**, 269-278.

Farges, F., Ponander, C.W., Calas, G. and Brown, G.E., 1992. Structural environments of incompatible elements in silicate glass/melt systems. II. U(IV), U(V), and U(VI). *Geochimica et Cosmochimica Acta*, **56**, 4205-4220.

Jaques, A.L., Jaireth, S. and Walshe, J.L., 2002. Mineral systems of Australia: an overview of resources, settings and processes. *Australian Journal of Earth Sciences*, **49**, 623-660.

Knutson, J., 1989. East Australian volcanic geology. *In*: W. Johnson R., J. Knutson and R. Taylor S. (Editors), *Intraplate volcanism in eastern Australia and New Zealand.*, Cambridge Univ. Press, pp. 89-107.

Lambert, I., Jaireth, S., McKay, A. and Miezitis, Y., 2005. Why Australia has so much uranium. *AusGeo News*, **80**, 7-10.

Larsen, L.M. and Sørensen, H., 1987. The Ilimaussaq intrusion-progressive crystallization and formation of layering in an agpaitic magma. *Geological Society of London Special Publication*, **30**, 473-488.

McKay, A.D. and Miezitis, Y., 2001. Australia's uranium resources, geology and development of deposits. *AGSO-Geoscience Australia, Mineral Resource Report 1*.

McLaren, S., Sandiford, M. and Powell, R., 2005. Contrasting styles of Proterozoic crustal evolution: A hot-plate tectonic model for Australian terranes. *Geology*, **33**, 673-676.

Mysen, B.O., Cody, G.D. and Smith, A., 2004. Solubility mechanism of flourine in peralkaline and meta-aluminous silicate glasses and in melts to magmatic temperatures. *Geochimica et Cosmochimica Acta*, **68**, 2745-2769.

Peiffert, C., Cuney, M. and Nguyen-Trung, C., 1994. Uranium in granitic magmas: Part 1. Experimental determination of uranium solubility and fluid-melt partition coefficients in the uranium oxide-haplogranite-H_2O-Na_2CO_3 system at 720-770^oC, 2 kbar. *Geochimica et Cosmochimica Acta*, **58**, 2495-2507.

Peiffert, C., Nguyen-Trung, C. and Cuney, M., 1996. Uranium in granitic magmas: Part 2. Experimental determination of uranium solubility and fluid-melt partition coefficients in the uranium oxide-haplogranite-H_2O,-NaX (X = Cl, F) system at 770°C, 2 kbar. *Geochimica et Cosmochimica Acta*, **60**, 1515-1529.

Plant, J.A., Simpson, P.R., Smith, B. and Windley, B.F., 1999. Uranium ore deposits: products of the radioactive earth. *Reviews in Mineralogy and Geochemistry*, **38**, 255-319.

Rogers, J.J.W. and Adams, J.A.S., 1969. Uranium. *In*: K.H. Wedepohl (Editor), *Handbook of Geochemistry*, Springer-Verlag, pp. 11-17.

Rogers, J.J.W., Ragland, P.C., Nishimori, R.K., Greenberg, J.K. and Hauck, S.A., 1978. Varieties of granitic uranium desposits and favorable exploration areas in the eastern United States. *Economic Geology*, **79**, 1539-1555.

Schofield, A., 2009a. Uranium content of igneous rocks of Australia: Map 1. Igneous rock type: surface geology, 1:5 000 000 scale, Geoscience Australia, Canberra.

Schofield, A., 2009b. Uranium content of igneous rocks of Australia: Map 2. Average uranium abundance: surface geology, 1:5 000 000 scale, Geoscience Australia, Canberra.

Schofield, A., 2009c. Uranium content of igneous rocks of Australia: Map 3. Average uranium abundance: solid geology, 1:5 000 000 scale, Geoscience Australia, Canberra.

Simpson, P.R., Brown, G.C., Plant, J. and Ostle, D., 1979. Uranium mineralization and granite magmatism in the British Isles. *Philosophical Transactions of the Royal Society of London*, **291**, 385-412.

Skirrow, R.G., Jaireth, S., Huston, D.L., Bastrakov, E., Schofield, A., van der Wielen, S.E. and Barnicoat, A.C., 2009. Uranium mineral systems: Processes, exploration criteria and a new deposit framework. *Geoscience Australia Record 2009/20*, 44pp.

Sun, S.S. and McDonough, W.F., 1989. Chemical and isotope systematics of oceanic basalts: implications for mantle composition and processes. *In*: A.D. Saunders and M.J. Norry (Editors), *Magmatism in the Ocean Basins*, Geological Society of London Special Paper 42, pp. 313-345.

Wall, V.J., 2006. Unconformity-related uranium systems: Downunder and over the top. *AESC Mebourne Extended Abstracts*.

Watson, E.B. and Harrison, T.M., 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters*, **64**, 295-304.

Wyborn, L.A.I., Bastrakova, I.V. and Budd, A.R., 1998. Australian Proterozoic granites - characteristics, sources and possible mechanisms for derivation and emplacement. *AGSO Record 1998/33*, 47-49.

Wyborn, L.A.I., Heinrich, C.A. and Jaques, A.L., 1994. Australian Proterozoic mineral systems: essential ingredients and mappable criteria. *AusIMM Publication Series 5/94*, 109-115.

Appendix

SOLID GEOLOGY DATASETS:

New South Wales

- Scheibner, E. and Hayward, D., 1999. New South Wales State Geoscience Package. Geological Survey of New South Wales, Sydney.

Northern Territory

- Ahmad, M. and Scrimgeour, I.R., 2006. Geological map of the Northern Territory (1:2,500,000 scale map, 2006 edition). Northern Territory Geological Survey, Darwin.
- Donnellan, N. and Johnstone, A., 2004. Mapped and interpreted geology of the Tennant Region (1:500,000 scale map, First Edition). Northern Territory Geological Survey, Darwin and Alice Springs.
- Lally, J. and Doyle, N., 2005. Pine Creek Orogen 1:500,000 Solid Geology Interpretation, preliminary release. Northern Territory Geological Survey, Darwin.
- Rawlings, D.J., 2001. Tectonostratigraphy of the McArthur Basin (1:1,000,000 scale map, First Edition. Northern Territory Geological Survey, Darwin.
- Slater, K.R., 2000. Northwestern Musgrave block special 1:250,000 interpreted geology (First edition). Northern Territory Geological Survey, Darwin.
- Slater, K.R., 2000. Tanami 1:250,000 integrated interpretation of geophysics and geology (First Edition). Northern Territory Geological Survey, Darwin.
- Vandenberg, L.C., Johnstone, A., Donnellan, N., Green, M.G. and Crispe, A., 2004. Northern Arunta Region integrated interpretation of geophysics and geology, Northern Territory (1:500,000 scale map, First Edition). Northern Territory Geological Survey, Alice Springs.

Queensland

- Bain, J.H.C. and Draper, J.J., 1997. North Queensland Geology. Australian Geological Survey Organisation, Bulleting, 240, and Queensland Department of Mines and Energy, Queensland Geology, 9,600 pp.
- Geological Survey of Queensland, 2002a. North Queensland gold and base metal study, Stage 1 (Georgetown) geoscience (GIS) dataset. Department of Mines and Energy, Queensland, Brisbane.
- Geological Survey of Queensland, 2002b. South-east Queensland regional geoscience (GIS) dataset. Department of Mines and Energy, Queensland, Brisbane.
- Geological Survey of Queensland, 2003. North Queensland gold and base metal study, Stage 2 (Charters Towers) geoscience (GIS) dataset. Department of Mines and Energy, Queensland, Brisbane.
- Geological Survey of Queensland, 2005. Central Queensland region (Yarrol-Connors-Auburn) geoscience (GIS) dataset (version 2). Department of Mines and Energy, Queensland, Brisbane.
- Geological Survey of Queensland, SRK Consulting, ESRI Australia and Taylor, Wall and Associates, 2006. North-west Queensland mineral province geoscience (GIS) dataset. Department of Mines and Energy, Queensland, Brisbane.

South Australia

- Cowley, W.M. (compiler), 2006. Solid geology of South Australia. Department of Primary Industries and Resources, South Australia. Mineral Exploration Data Package, 15 (version 1.1).

Tasmania

- Brown, A.V., Calver, C.R., Clarke, M.J., Corbett, K.D., Everard, J.L., Forsyth, S.M., Goscombe, B.A., Green, D.C., Green, G.R., McClenaghan, M.P., Pemberton, J. and Vicary, M.J., 2007. 1:250,000 Digital Geology of Tasmania. Mineral Resources Tasmania, Hobart.

Victoria

- Simons, B.A. and Moore, D.H., 1999. Victoria 1:1,000,000 Pre-Permian Geology. Geological Survey of Victoria, Melbourne.

Western Australia

- Cassidy, K.F., Champion, D.C., McNaughton, N.J., Fletcher, I.R., Whitaker, A.J., Bastrakova, I.V. and Budd, A.R., 2002. The characterisation and metallogenic significance of Archaean granitoids of the Yilgarn Craton. Minerals and Energy Research Institute of Western Australia, Report 222.
- Geological Survey of Western Australia, 2001. 1:500,000 interpreted bedrock geology map of Western Australia, Geological Survey of Western Australia (June 2001).

SURFACE GEOLOGY DATASETS

All surface geology datasets used are available for download at:
http://www.ga.gov.au/minerals/research/national/nat_maps/nat_geol_maps.jsp#surface

New South Wales

- Raymond, O.L., Liu, S.F., Kilgour, P., Retter, A.J., Stewart, A.J. and Stewart, G., 2007. Surface geology of Australia 1:1,000,000 scale, New South Wales (Second Edition). Geoscience Australia, Canberra.

Northern Territory

- Liu, S.F., Raymond, O.L., Stewart, A.J., Sweet, I.P., Duggan, M.B., Charlick, C., Phillips, D. and Retter, A.J., 2007. Surface geology of Australia 1:1,000,000 scale, Northern Territory (First Edition). Geoscience Australia, Canberra.

Queensland

- Whitaker, A.J., Champion, D.C., Sweet, I.P., Kilgour, P. and Connolly, D.P., 2007. Surface geology of Australia 1:1,000,000 scale, Queensland (Second Edition). Geoscience Australia, Canberra.

South Australia

- Whitaker, A.J., Glanville, D.H., English, P.M., Stewart, A.J., Retter, A.J., Connolly, D.P., Stewart, G.A. and Fisher, C.L., 2008. Surface geology of Australia 1:1,000,000 scale, South Australia (First Edition). Geoscience Australia, Canberra.

Tasmania

- Raymond, O.L., Liu, S.F. and Kilgour, P., 2007. Surface geology of Australia 1:1,000,000 scale (Third Edition). Geoscience Australia, Canberra.

Victoria

- Raymond, O.L., Liu, S.F., Kilgour, P., Retter, A.J. and Connolly, D.P., 2007. Surface geology of Australia 1:1,000,000 scale, Victoria (Third Edition). Geoscience Australia, Canberra.

Western Australia

- Stewart, A.J., Sweet, I.P., Needham, R.S., Raymond, O.L., Whitaker, A.J., Liu, S.F., Retter, A.J., Connolly, D.P. and Stewart, G., 2008. Surface geology of Australia 1:1,000,000 scale, Western Australia (First Edition). Geoscience Australia, Canberra.

GEOCHEMICAL DATA

OZCHEM

- Champion, D.C., Budd, A.R., Hazell, M.S. and Sedgmen, A., 2007. OZCHEM National Whole Rock Geochemistry Database. Geoscience Australia, Canberra.
- Additional open file geochemical data were sourced from the Geological Survey of New South Wales, the Geological Survey of Queensland, the Northern Territory Geological Survey, and the Department of Primary Industries and Resources, South Australia.

MISCELLANEOUS DATASETS

MINLOC (mineral occurrences)

- Ewers, G., Evans, N. and Kilgour, B., 2001. MINLOC Mineral Localities Database. Geoscience Australia, Canberra.

OZMIN (Mineral deposits)

- Ewers, G., Evans, N., Hazell, M. and Kilgour, B., 2002. OZMIN Mineral Deposits Database. Geoscience Australia, Canberra.

Geological regions

- Blake, D.H. and Kilgour, B., 1998. Geological Regions. Geoscience Australia, Canberra.