The depositional mechanism for U in magmatic-related systems is problematic and poorly understood. Disseminated U hosted in magmatic-stage minerals is deposited via normal crystallisation of minerals from the melt. Suggestions for the depositional mechanism include fluid mixing, boiling, reduction and cooling (Skirrow et al., 2009). Other potential mechanisms may include pH change and decrease in the activity of ligands, such as decreased F activity due to the crystallisation of fluorite.

Intrusive-related uranium systems

Intrusive-related uranium systems appear to be uncommon globally. Two well known examples, the Ross Adams and Kvanefjeld deposits, will be briefly described here. Although perhaps the best known deposit associated with igneous rocks, the alaskite-hosted Rössing U deposit is not considered here, due to persisting uncertainties regarding the genesis of the deposit. The interpreted genetic model for U mineralisation at Rössing and the surrounding regions is related to the intrusion of Cambrian alaskitic pegmatites during the final stages of peak metamorphism (Kinnaird and Nex, 2007). Initial Sr isotope ratios indicate that these are crustally derived (Nex et al., 2002). Increasing U content is not correlated with other elements, which suggests that fractional crystallisation was not the mechanism for U enrichment (Nex et al., 2001; Kinnaird and Nex, 2007). However, this may also be due to post-magmatic disruption of primary U contents. Calculated zircon saturation temperatures reveal low magmatic temperatures (~675-700 degrees, McDermott et al., 1996).

The evidence given above has been interpreted to suggest that the U-rich alaskites in the Rössing area were produced via low degree partial melting of a uraniferous source region (for example, see Cuney and Kyser, 2008). At Rössing, U was remobilised and concentrated post-alaskite emplacement by fluids during the (?)Cretaceous, crystallising as secondary beta-uranophane (Nex et al., 2002). Although evidence suggests fractionation did not play a major role, the geochemical features of the alaskites are not dissimilar to strongly fractionated granites if a high degree of post-magmatic U redistribution is taken into account. Thus, several questions still remain regarding the Rössing deposit, especially regarding source region, U deposition and the genetic model. Therefore, Rössing-style mineralisation will not be targeted in this investigation.

THE ROSS ADAMS DEPOSIT

The Ross Adams deposit is genetically related to the Jurassic Bokan Mountain Granite Complex, which is situated on Prince of Wales Island, south-eastern Alaska, and was discovered in 1955 as a radiometric anomaly. 89,000 tonnes of ore have been mined from Bokan Mountain, predominately from the Ross Adams deposit (Cuney and Kyser, 2008). Ore at Ross Adams consists of uranothorite, uraninite and less than 2% sulphides (Thompson, 1988).

The Bokan Mountain Granite Complex is a multi-stage peralkaline ring dyke complex (Thompson et al., 1982). A U-Pb zircon age of 171±5 Ma has been obtained (De Saint-Andre et al., 1983), which differs somewhat from a whole-rock Rb-Sr age of 151±5 reported by Armstrong (1985). Twelve separate lithologies have been recognised, although riebeckite granite porphyry constitutes the dominant rock type (Thompson et al., 1982; Thompson, 1988). Ore is closely associated with albited aegerine syenite, and forms pipe-like bodies along contacts, or as pods in shear zones (Thompson, 1988). An extensive network of fluorite-bearing veins extending up to 2.6 km from the eastern margin of the intrusion contains U-Th-REE mineralisation, with U grades of up to 2.8% (Staatz, 1978).
The Granite Complex is post-tectonic, and was emplaced at a shallow crustal depth (Thompson, 1988). As with many peralkaline granites, the ultimate magma source is thought to have been within the upper mantle (Thompson et al., 1982). Geochemically, the granites are characterised by high Na+K/Al, ranging from 0.9 to 2.08, with Na₂O>K₂O in all granite types (Thompson et al., 1982). Uranium content is only moderate, with an average of 12 ppm in unaltered granite (Cuney and Kyser, 2008).

The timing of mineralisation is closely associated with intrusion stage 2, which involved significant devolatilisation of the magma (Thompson et al., 1982; Thompson, 1988). Oxygen and carbon isotope analyses of hydrothermal calcite indicate that the fluids causing the alteration associated with mineralisation are of a magmatic origin (Thompson, 1988). The co-crystallisation of fluorite with calcite as an alteration mineral, fluorite-bearing veins, and the overall high F content of the magma strongly suggests that may have been important in transporting U as fluoro complexes. This fluid flow was concentrated in zones of structural weakness, such as zones of competency contrast and syn-magmatic faults. Uranium deposition may have occurred when these F complexes were destabilised.

THE KVANEFJELD DEPOSIT

The Middle Proterozoic Ilímaussaq alkaline igneous complex in southern Greenland forms part of the Gardar Igneous Province. Three major intrusive phases may be recognised, comprised of a number of exotic lithologies (for a summary of these, see Sørensen, 2001). These were emplaced at a shallow crustal level (2-3 km; Sørensen, 2001). The Kvanefjeld U deposit, discovered in 1956, is hosted by steenstrupine lujavrites of the Ilímaussaq alkaline complex (Nielsen and Steenfelt, 1979). Initial drilling in the 1970s identified 27 000 reasonably assured tonnes of U, mostly hosted by steenstrupine (Na₁₄Ce₆Mn₂Fe₂(Zr, Th, U)(Si₆O₁₈)(PO₄)₇·3H₂O; Cuney and Kyser, 2008).

Bailey et al. (2001) provide a summary of the geochemistry of the Ilímaussaq alkaline complex. The most prominent features of the nepheline syenites, of which the lujavrites are part, are high Na+K/Al, high field strength elements (Zr, Hf, Nb, Ta, Th, U, Pb), rare earth elements, Sn, Li, Be, Rb, Zn, Sb, W, Mo, As and Ga, and low Ba, Sr, and transition metal elements (Co, Cu, Ni, Sc, V and Cr) except Zn.

The distinctive geochemical characteristics of the Ilímaussaq alkaline complex can be explained by extreme fractional crystallisation within a closed system (>99% fractionation; Bailey et al., 2001). The parental magma is thought to be an alkali basalt magma chamber deep in the crust, (Sørensen and Bailey, 2006). Basalts in the Ilímaussaq region contain higher alkalis, P, Ba, Sr, Nb and LREE than other basalts in the Gardar province, reflecting melting of an enriched mantle source (Sørensen, 2001). Such a source may also play an important role in the genesis of the Ross Adams deposit, as suggested by the presence of subduction-related alkali basalt magmatism preceding granite intrusion (Thompson et al., 1982).

MINERAL SYSTEMS MODEL FOR INTRUSIVE-RELATED URANIUM SYSTEMS

The mineral systems model for intrusive-related uranium systems is relatively simple, and is largely governed by well-known igneous processes. The two deposits described above are intimately associated with peralkaline magmatism originating from partial melting of the upper mantle followed by extreme fractional crystallisation. Although peralkaline rocks are some of the most prospective for intrusive-related U systems, other crustally-derived granite types, including high temperature I-type and A-type magmas, may also be highly prospective, as these are commonly high
in U and F (Plant et al., 1999). The tectonic setting in which these magmas are generated and emplaced is typically anorogenic or extensional, but this may not be the case universally.

S-type granites, derived from partial melting of sedimentary or supracrustal rocks (Chappell and White, 2001), are considered to be comparatively unimportant in the genesis of intrusive-related U systems targeted in this study (Plant et al., 1999). This may be due to the melting of U-poor source rocks, U remaining in the granite source region (Sawka and Chappell, 1986; 1987) or, if magmatic temperature is low, a significant quantity of U being locked within restite phases (such as zircon; Chappell et al., 2000), thus rendering it unavailable to concentration with fractionation. While U-bearing alaskites at Rössing are interpreted to be derived from partial melting of sedimentary rocks (Berning et al., 1976; McDermott et al., 1996), the uncertainties mentioned above regarding this deposit prevent the development of a suitably robust mineral systems model.

The U content of the magma will be governed by the residual mineralogy in the source region and initial U concentration immediately following partial melting. Elevated U concentration in the original melt is favoured where the source region is enriched, such as metasomatised mantle. Magmatic evolution processes, specifically fractional crystallisation, are critical in concentrating U in the melt as it ascends through the crust, and both the Bokan Mountain Granite Complex and Ilímaussaq intrusions have been highly fractionated, with U more highly concentrated in the most differentiated magmas. Although U is largely incompatible in the structure of the main rock forming minerals, and hence is concentrated with their removal during fractionation, it is able to be accommodated into a wide range of accessory minerals, such as titanite, zircon and monazite in relatively low concentrations (Bea, 1996). High U solubilities within the melt prevent the early partitioning of U into accessory phases at an early stage.

A peralkaline bulk rock composition, such as that which characterises the Bokan Mountain and Ilímaussaq intrusions, is the most effective chemical mechanism for maintaining U solubility. Uranium solubility is also enhanced by high halogen contents (Peiffert et al., 1996). In cases where U solubility is extremely high, abundant uraninite will not form, and U may be partitioned into refractory minerals (Cuney and Kyser, 2008). These present metallurgical complications and extraction of U from such minerals may be difficult and costly.

Uranium may occur within disseminated U-rich minerals throughout an igneous body, or may be present within veins, such as the I and L vein system at Bokan Mountain (Staatz, 1978). Fractionation alone is unlikely to be sufficient to generate economic grades of U. Rather, fluid-mediated processes are probably extremely important, and examples of this style of U mineralisation show evidence of sub-solidus or later remobilisation of U. As discussed above, U may be transported by Cl- or F-rich magmatic-hydrothermal fluids. The precipitation of U from these fluids in veins presents a more favourable target for exploration, since these will be higher grade, and U may be easier to extract. Therefore, mineralisation may occur at some distance from the igneous body in a country rock host.

The mineral systems model used here for intrusive-related U systems is presented diagrammatically in Figure 4. Based on Figure 4 and the discussion above, the following features are considered characteristic of these mineral systems:
Potential for magmatic-related uranium mineral systems in Australia

Figure 4: Schematic illustration of the mineral systems model used for intrusive-related U systems.
Source magma

The source magma component reflects the relative importance of certain magma types in the genesis of intrusive-related U deposits. Most often, these are of a broadly felsic composition, since mafic magmas are typically low in U (see above). Both the Bokan Mountain Granite Complex and the Ilímaussaq intrusions are characterised by a peralkaline bulk rock affinity. The high alkali contents of these magmas produce extremely high U solubilities, which in turn allow U to be strongly concentrated with fractional crystallisation. Hence, peralkaline igneous units are highly prospective, but are unfortunately uncommon in Australia.

As well as peralkaline magmas, some types of crustal melts are also prospective. These have the additional advantage of being sourced from material which has undergone a prior phase of U concentration. In particular, A- and I-type magmas may also have potential for generating magmatic-related U systems (see above). Prospectivity is enhanced when magmatic temperature is high, as this enables U-bearing minerals in the magma source region to be broken down, liberating U into the melt. High magmatic temperatures also slightly increases U solubility (Peiffert et al., 1994). To maintain high U solubility, non-peralkaline magmas require high concentrations of halogens.

The following criteria are considered important to this mineral systems component:
- The distribution of high temperature, high halogen A- or I-type magmas
- The distribution of peralkaline magmas
- The distribution of igneous rocks of a generally felsic composition

Uranium concentration processes

Magmatic concentration of U is facilitated most prominently by fractional crystallisation, and both the Ross Adams and Kvanefjeld U deposits are hosted by the extreme fractionation products of a parental magma. This process will manifest itself in high magmatic concentrations of U and other associated elements including, but not necessarily always, other HFSE. Since U is mobile under a range of conditions, and is therefore susceptible to be modified, observed concentrations are potentially not reflective of true values. An independent means of quantifying the level of enrichment of U and related elements may also be given by examining selected HFSE (Zr, Nb and Y) contents of a rock.

The following criteria are considered important to this mineral systems component:
- Geochemical indicators suggesting a high degree of fractional crystallisation has occurred
- High average U content
- High average content of high field strength elements (HFSE)

Uranium depositional processes

As discussed previously, the depositional mechanism of U in magmatic-related systems is poorly understood. In the absence of a firm understanding of process, direct evidence of anomalous U concentration may be used to highlight areas where U deposition has occurred. For this study, the following criterion is used:
- High U radiometric anomalies
PROSPECTIVITY ANALYSIS METHODOLOGY FOR INTRUSIVE-RELATED URANIUM SYSTEMS

The following section describes the methodology used to determine the prospectivity for intrusive-related U systems at a national scale. The final prospectivity map is a function of eight individual criteria maps, which will now be discussed.

Source magma

Intrusive composition

Intrusive geological units were extracted from the national surface geology dataset (Raymond et al., 2009) on the basis of their lithological group, as specified within the dataset. Fuzzy membership values based on their bulk composition (Table 2) were subjectively assigned and used to produce the compositional criterion map. Initial fuzzy membership values assigned were determined to have a disproportionate influence on the final prospectivity result for the relative importance of this criterion. The values were therefore adjusted using a scaling factor of 0.7. Although it is typically only felsic compositions which are prospective for intrusive-related U systems, low fuzzy membership values have also been assigned to intermediate compositions in order to allow for modest potential (for example, due to the presence of localised felsic differentiates).

Table 2: Fuzzy membership values assigned to intrusive rocks based on their composition. The initial fuzzy membership values assigned are shown in the second column. The final fuzzy membership values used are in the third column.

<table>
<thead>
<tr>
<th>COMPOSITIONAL CLASS</th>
<th>FUZZY MEMBERSHIP VALUE 1</th>
<th>FUZZY MEMBERSHIP VALUE 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultramafic to mafic</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Intermediate to mafic</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>Unknown</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>Intermediate</td>
<td>0.25</td>
<td>0.18</td>
</tr>
<tr>
<td>Mixed (felsic to mafic)</td>
<td>0.50</td>
<td>0.35</td>
</tr>
<tr>
<td>Felsic to intermediate</td>
<td>0.70</td>
<td>0.49</td>
</tr>
<tr>
<td>Felsic</td>
<td>1.00</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Magmatic affinity

Peralkaline rocks were attributed with a fuzzy membership value on the basis of their peralkalinity (that is, their Na+K/Al value). Due to the mobility of alkali elements under a range of conditions (see Rollinson, 1993 and references therein), a level of uncertainty is introduced, and fuzzy values are assigned for all samples with Na+K/Al > 0.95, with values greater than one having a fuzzy membership value of one. The relationship used to determine the specific fuzzy membership value is shown below in Figure 5. For non-peralkaline rocks, specific granite type was determined on the basis of geochemistry. The very limited number of samples which have been categorised as I-, S- or A-type necessitates the use of other approaches to determine granitoid type.

Whalen et al. (1987) proposed several discrimination diagrams to distinguish granitoids with an A-type affinity on the basis of their chemical composition. Three of these diagrams (Figure 6) have been used to assess the A-type character of individual geochemical analyses:

1. 10 000Ga/Al versus Zr;
2. Zr+Nb+Ce+Y versus Na2O+K2O/CaO; and
3. 10 000Ga/Al versus Na2O+K2O/CaO.
Each geochemical sample was assessed against these discrimination diagrams to return a binary result (1 = positive A-type affinity, 0 = no affinity). The final probability was calculated as the number of positive results returned divided by three.

**Figure 5:** Relationship defining the fuzzy membership value for peralkaline magmas. The steepness of the line does not reflect any relationship relating to U solubility. Rather, it is intended to account for potential analytical uncertainties.

**Figure 6:** A-type discrimination diagrams from Whalen et al. (1987) used in this report to determine A-type affinity. Average A-type compositions from Whalen et al. (1987) and King et al. (1997) are also shown.
Classification of samples into I- and S-type affinities is more problematic. Criteria have been developed from Chappell and White (2001) to assign probabilities. These criteria are:

- **Mineralogical:** sample description contains “hornblende” (I-type).
- **Normative mineralogy:** I-type granitoids have normative diopside and <1% normative corundum, while S-type granitoids contain >1% normative corundum.
- **Chemical:** Samples with an aluminous saturation index (ASI) < 1.0 at SiO$_2$ contents less than 72 wt.% are classified as I-types, while an ASI>1.1 denotes an S-type.

While other criteria may be of use in the determination of classification type, the scale and scope of this study does not permit a more detailed analysis. In some cases, classification may be complicated by a number of factors. For example, weathering may strongly influence the calculated ASI. Nevertheless, the classification scheme presented above is deemed to be sufficient for the purposes of this investigation.

Fuzzy membership values were assigned by multiplying the assigned probabilities by the maximum value available (A- and I-type = 1.0, S-type = 0.2). These have been further modified by the magmatic temperature. Magmatic temperature is approximated by the zircon saturation temperature ($T_{zr}$), which has been calculated according to Watson and Harrison (1983). Fuzzy membership values were then assigned to samples with $T_{zr}$>650°C by a linear function (Figure 7). For samples with insufficient data to calculate $T_{zr}$, the modal $T_{zr}$ was attributed (775°C). The fuzzy membership values for granitoid type and temperature were combined using the fuzzy algebraic product operator, since low magmatic temperature will decrease the potential of the rock.

Uranium solubility in non-peralkaline granites is strongly influenced by high halogen concentrations. While both Cl and F are able to increase U solubility, only F is considered here, due to the paucity of Cl data in the geochemistry used and the propensity of Cl to partition into the volatile phase, thus preventing representative determination of the actual Cl content of the magma. Furthermore, F is considered to perform a more important role than Cl in producing high U solubility (Peiffert et al., 1996). In peralkaline magmas, high alkali contents are significantly more important than halogens, and thus they are not considered for those magmas. To determine fuzzy membership values relating to F-enhanced U solubility, percentiles were calculated for the available F data, and assigned values (Table 3). Fuzzy membership values for F content were used to further modify the fuzzy membership value of non-peralkaline rocks by combining the two using the fuzzy algebraic sum operator. This operator has been used so as to increase the potential if high F is present, rather than decreasing it if it is not.