Potential for intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia

A continental-scale analysis of mineral system prospectivity

Dulfer, H., Skirrow, R.G., Champion, D.C., Highet, L.M., Czarnota, K., Coghan, R. and Milligan, P.R.
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ISSN 2201-702X (PDF)

ISBN 978-1-925124-94-1 (PDF)

GeoCat 83884


Front cover photographs: Top right image: extract from map of Australia's potential for intrusion-hosted Ni-Cu-PGE sulfide deposits (from this Geoscience Australia Record). Left image: Exploration drilling at the Nebo-Babel deposit, Musgrave Province, Western Australia. Image with permission from Cassini Resources (www.cassiniresources.com.au). Lower centre image: polished slab of Ni-Cu massive sulfide ore (image courtesy Dean Hoatson), with Australian 5 cent coin for scale (composed of 75% Cu, 25% Ni; image from www.wikipedia.com). Lower right image: Russian ingot of 95.95% pure palladium metal. Image from Johnson Mathey PLC Media Library.
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Executive summary

Magmatic mineral deposits of nickel, copper and the platinum-group elements (Ni-Cu-PGE) form by the immiscible separation and concentration of Ni-Cu-PGE-rich sulfide liquids from magmas of mantle origin. An important sub-type of these deposits is the tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposit class, typified by the giant Noril'sk (Russia), Voisey's Bay (Canada) and Jinchuan (China) deposits. These contribute significant proportions of the world’s production of Ni and PGEs, and represent some of the most valuable mineral deposits on Earth. However, there are very few known tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia, and these are mostly uneconomic due to small size, low grade and/or remoteness.

This continental-scale study of the potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia addresses the problem of whether the apparent under-representation of resources of this type in Australia is due to lack of geological endowment or is a consequence of concealment of mineral deposits by sediments, basins and regolith (cover) which has hindered exploration success.

This study is the first continental-scale assessment of Ni-Cu-PGE mineral potential of Australia to apply a knowledge-driven GIS-based prospectivity analysis method. A mineral systems approach is used to identify new mineral provinces as well as extensions to known provinces with potential to host major Ni-Cu-PGE sulfide deposits.

Major Ni-Cu-PGE sulfide deposits are consequences of lithospheric-scale earth processes, and form where there was a coincidence of ore-forming processes in space and time. Ore formation required four components of the mineral systems to have operated efficiently, namely: (1) energy sources or drivers of the ore-forming system; (2) crustal and mantle lithospheric architecture; (3) sources of ore metals (i.e., Ni, Cu, PGE in this study); and (4) gradients in ore depositional physico-chemical parameters. Conceptual criteria were developed that represent essential geological processes involved in each of the four components of the mineral system. These were translated into practical, mappable, criteria for which proxy geoscientific datasets were developed. Maps of favourability were constructed for each of the four system components. These were created using overlays of input rasters that were weighted (using a fuzzy logic-based method) according to the perceived importance, applicability and confidence level of each input dataset in the mineral system analysis. The results for the four maps were allowed to contribute equally to the final mineral potential map so that the areas of highest potential represent targets where all four mineral system components combine most favourably.

The GIS analysis of prospectivity uses a wide range of existing and newly developed continental- to regional-scale geological, geophysical and geochemical datasets, including: the Australian Mafic-Ultramafic Magmatic Events GIS dataset; Proterozoic Large Igneous Provinces of Australia dataset; AuSREM seismic velocity data for the mantle; boundaries of crustal blocks based on seismic reflection and neodymium isotope model age data; the OZCHEM whole-rock geochemistry database; National Geochemical Survey of Australia data; mineral occurrence data; and gravity and magnetic data. A key innovation was the joining of digital map data in the Mafic-Ultramafic Magmatic Events GIS with point data in the OZCHEM geochemistry database via the Australian Stratigraphic Index Database. This has enabled extrapolation of geochemical point data to solid-geology and surface-geology map polygons representing mafic-ultramafic units as well as magmatic events across Australia.
The assessment predicts high potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in a wide range of geological regions of Australia, including those of known prospectivity and several with previously unrecognised potential. The results strongly suggest that the current deficit of large economic deposits of tholeiitic intrusion-hosted Ni-Cu-PGE sulfides in Australia is due not to a lack of geologically favourable settings but is more likely an apparent deficit due to difficulties in discovering such deposits in greenfields regions where prospective geology is concealed by cover. Importantly, the districts hosting the few known major intrusion-hosted Ni-Cu-PGE sulfide deposits were successfully predicted with high potential, despite non-inclusion of these deposits as inputs in the modelling (to avoid biasing the results). When applied with a robust scientific framework and high-quality input datasets the knowledge-driven mineral systems approach is a powerful tool to predict mineral potential in regions where there are no known mineral deposits of the type sought. The approach also permits predictions in areas where prospective basement is concealed by cover, because many of the input datasets (e.g., geophysical data, solid geology) represent geological features beneath the cover. Nevertheless, gaps in data coverage and limitations in the spatial and temporal resolution of some input datasets mean that the results should be used to aid exploration targeting at craton- to regional-scale (rather than deposit-scale) and to identify areas and magmatic events worthy of acquisition of additional data to ground-truth the prospectivity assessment. The study does not attempt to identify individual prospective intrusions or parts of intrusions containing the ore deposits themselves.

In addition to this report, the results of the study are available as a series of Geodatabase digital maps (rasters) representing (1) the input datasets, (2) four mineral system components, and (3) the final prospectivity for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits. The Python programming script used in the GIS analysis is also available. Finally, the primary digital data used to create the input datasets for the modelling are available on-line for users’ own purposes.
1 Introduction

1.1 Australia’s nickel resources: known and undiscovered

The world distribution and ages of significant nickel (Ni) sulfide and platinum-group element (PGE) deposits is shown in Figure 1.1. Archean komatiite-hosted nickel sulfide deposits are Australia’s principal source of current nickel production (Figure 1.1, e.g., Kambalda), contributing to Australia’s ranking as the 6th largest in nickel production in the world (USGS, 2015). By comparison, tholeiitic intrusion-hosted nickel-copper-PGE deposits, typified by the Noril’sk, Voisey’s Bay and Jinchuan deposits (Figure 1.1), contribute a major proportion of current world production of nickel. Resources of Ni, PGE and copper (Cu) are shown in Figure 1.2 for major deposits including those in Australia. The Ni-Cu-PGE deposits of the Noril’sk district in Russia constitute one of the world’s most valuable mineral resources, valued at approximately AUD$1 trillion based on total resources (past production plus unmined resources; Naldrett, 2004) and current commodity prices.

![Figure 1.1 Nickel sulfide and nickel laterite deposits, and ages (Ga). The major nickel sulfide deposits partly hidden behind the symbol for Kambalda (1.4 Mt global resource of nickel) in Western Australia are Mount Keith (~3.4 Mt), Perseverance (~2.5 Mt), Yakabindie (~1.7 Mt), and Honeymoon Well (~1 Mt). Figure reproduced from Hoatson and Lewis (2014), with the distribution of laterite deposits after Elias (2002) and the ages of deposits from Hoatson et al. (2006).](image-url)
Figure 1.2 Bar chart of global resources of PGEs (red), Ni (green), and Cu (blue) metal in the major PGE-Ni-Cu and Ni-Cu-PGE deposits and mining camps of the world. Australian deposits are shown in bold font, overseas deposits in normal font. All of the deposits between the Great Dyke and Nebo-Babel inclusive are tholeiitic intrusion-hosted deposits, including large layered mafic-ultramafic intrusions (Great Dyke to Panton) and mafic-dominated generally massive intrusions (Pechenga to Nebo-Babel). Komatiite-hosted deposits are shown from Kambalda to Raglan, inclusive. Noril’sk and Duluth are shown separately as examples of continental flood basalt-associated deposits. The Sudbury deposits, also shown separately, are meteorite impact-related. Deposits between Thompson and Lac des Iles (inclusive) are of hydrothermal or metamorphic type. Global resource data from Naldrett (2004), and Hoatson et al. (2006). Figure modified from Hoatson and Lewis (2014).

Although Australia holds the largest economic resources of nickel in the world (25%; Britt et al., 2014; USGS, 2015), the vast majority of this inventory is contained within lateritic and komatiitic deposits (Figure 1.3). Ongoing metallurgical issues with lateritic Ni deposits has limited their development in Australia although this is slowly changing. Komatiite-hosted Ni sulfide deposits are attractively high grade but individually and collectively represent small to medium sized resources of Ni (Figure 1.2, see deposits from Kambalda to Raglan, inclusive). Conversely, tholeiite intrusion-hosted Ni-Cu-PGE sulfide deposits may be of immense value due their size, multi-commodity composition and long mine lives. These advantages are counter-balanced by the relative scarcity of giant deposits of this type globally.
The known resources of tholeiitic intrusion-hosted nickel-copper-PGE in Australia are relatively small (Figure 1.3). The undeveloped Nebo-Babel deposit (Musgrave Province, central Australia; Seat et al., 2007, 2009, 2011) and Nova-Bollinger deposits discovered in 2012 (Albany-Fraser Orogen, Western Australia; IGO, www.igo.com.au) are the most significant known examples of this deposit type in Australia. The Nova-Bollinger deposits contain a resource of 14.3 Mt @ 2.3% Ni and 0.9% Cu (IGO, 2015, www.igo.com.au), and the Nebo-Babel deposit contains 203 Mt @ 0.4 Ni and 0.4% Cu (Cassini Resources, 2015, www.casiniresources.com.au).

Figure 1.3 Locations of major nickel deposits of Australia shown by type of deposit. The coloured geology polygons show the distribution of mafic and ultramafic rocks (coloured by event) from the Australian Mafic-Ultramafic Magmatic Events GIS dataset (Thorne et al., 2014).
1.2 Rationale and aims: a national assessment of Ni-Cu-PGE sulfide mineral potential

The brief review of Ni resources above highlights the apparent under-representation of tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia relative to other continents. This raises the question of whether this is due to low geological endowment or, conversely, is the result of limitations on discovery due to concealment of deposits by extensive regolith and sedimentary basin cover, remoteness, and other non-geological factors. A primary aim of the current study is to address this important question of endowment versus discoverability. The results show that Australia does indeed have significant geological potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits. Therefore, a key challenge in unlocking this mineral potential is to recognise the signs of major Ni-Cu-PGE ore-hosting mineral systems through the cover, particularly in under-explored ‘greenfield’ regions of Australia.

Exploration for intrusion-hosted Ni-Cu-PGE deposits is challenging partly because the dimensions of even the larger deposits may be only a few hundred metres in width and up to 2-4 km in length (e.g., Naldrett, 2004). Yet these sulfide deposits are ‘symptoms’ of much larger ore-forming systems, or mineral systems, that involve geological processes at scales ranging from deposit through regional to craton (Wyborn et al., 1994). By considering a mineral system at broader scales the explorationist may have increased probability of detecting a part of an ore-forming system. Once such a region or district or intrusive complex is identified, techniques for area reduction and ‘vectoring’ towards mineralisation can be applied (e.g., McCuaig et al., 2010).

In this study a continental scale of analysis was undertaken because giant Ni-Cu-PGE sulfide deposits are expressions of lithospheric-scale ore-forming geological systems, involving melting of the mantle and transfer of magmas through the lithospheric mantle and crust to the sites of crystallisation and ore formation within the mid- to upper crust. The scale of such ore-forming systems is sufficiently large that some features of the geological settings are expected to be recognisable in continental-scale geological, geophysical and geochemical datasets. The recent availability of a suite of new digital datasets at continental scale, such as the Mafic-Ultramafic Magmatic Events of Australia GIS dataset (Thorne et al., 2014), the AuSREM model of seismic tomography (Kennett et al., 2013), Major Crustal Boundaries of Australia (Korsch and Doublier, 2014), and a Geochemical Classification of Mafic and Ultramafic rocks in Australia (Champion and Dulfer, 2015), has provided the opportunity to attempt such a study at the continental scale for the first time.

A key objective of the study is to identify new mineral provinces in Australia with previously unrecognised potential for giant or major Ni-Cu-PGE sulfide deposits, focussing on tholeiitic intrusion-hosted nickel-copper-PGE sulfide ore-forming systems. As noted above, these systems are of potentially world-class size and value and, therefore, can have a major impact economically for Australia. The scope of the present national-scale study does not extend to identification of individual prospective intrusions or parts of intrusions hosting ore deposits. Rather, prospective regions are identified in this study that are considered worthy of more detailed follow-up by exploration companies and others to acquire more data and to ascertain the presence (or otherwise) of economic mineralisation.
1.3 Foundation datasets

Geoscience Australia has modelled the spatial patterns of mineral potential using ESRI Arc GIS tools and knowledge-driven fuzzy logic-based methods as explained in the report. The prospectivity analysis uses a wide range of geological, geophysical and geochemical datasets as proxies for fundamentally important geological features in the Ni-Cu-PGE ore-forming mineral systems. The principal digital datasets used to derive the proxy datasets for the modelling are listed below. Several of these build on earlier work by Geoscience Australia, in particular: reports and maps in Adobe pdf format on Australian Archean and Proterozoic mafic-ultramafic events (Hoatson et al., 2008, 2009); Proterozoic Large Igneous Provinces maps in pdf format and accompanying report (Claoué-Long and Hoatson, 2009); and a major report on platinum-group element deposits in Australia (Hoatson and Lewis, 2014). The Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al., 2014) was developed as a digital spatial database from the earlier pdf-format maps and extended from the Archean and Proterozoic into the Phanerozoic. The resultant dataset has been fundamental to the present study and provides a time-based framework of mafic-ultramafic magmatism and associated mineralisation for the Australian continent. Summaries of some of the data are presented in Figure 1.4, Figure 1.5 and Figure 1.6.

http://dx.doi.org/10.4225/25/550F880BA5AF1
http://dx.doi.org/10.4225/25/550F880BA5AF1
http://dx.doi.org/10.4225/25/54125552CDA7C
1.4 Digital information products

The package of digital information of this study of Australia’s potential for intrusion-hosted Ni-Cu-PGE sulfide deposits includes: (1) this Geoscience Australia Record which documents the geological and theoretical basis for the study, the prospectivity mapping methodology, the input data layers, and the results; (2) published GIS datasets that were used as inputs in the analysis (listed above, section 1.3); (3) Geodatabase rasters of all input data maps, a set of maps from an intermediate step in the prospectivity analysis (for each of the four mineral system components), and the final prospectivity map; and (4) the Python programming script used to run the GIS analysis.

Users may use the results of this analysis directly in broad-scale exploration targeting, or alternatively may use the digital data layers separately for their own purposes.

1.4.1 Geodatabase digital map products of this study


1.4.2 Python programming script for GIS modelling

Figure 1.4 Time-space-event chart of Australian Archean mafic-ultramafic magmatic events and related mineralisation including global examples. From Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al., 2014).
Figure 1.5 Time-space-event chart of Australian Proterozoic and Phanerozoic mafic-ultramafic magmatic events and related mineralisation including global examples. From Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al., 2014).
Figure 1.6 Map of Australian Archean, Proterozoic, and Phanerozoic mafic-ultramafic magmatic events. From Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al., 2014).
2 Formation of magmatic Ni-Cu-PGE sulfide ore deposits

2.1 Model of magmatic Ni-Cu-PGE sulfide ore-forming systems

Nickel-Cu-PGE sulfide ores are orthomagmatic mineral deposits that form by the separation and concentration of Ni-Cu-PGE-rich immiscible sulfide liquids from komatitic, picritic and tholeiitic basaltic magmas (e.g. Arndt et al., 2005). Figure 2.1 shows a lithospheric-scale model of the geological settings and key components of Ni-Cu-PGE sulfide ore-forming systems based on a synthesis of published information on the world’s major nickel-copper-PGE deposits and their host magmatic systems, in particular: Naldrett (2004), Arndt et al. (2005), Barnes and Lightfoot (2005), Hoatson et al. (2006), Begg et al. (2010), Schulz et al. (2010), Griffin et al. (2013), and Arndt (2013). A range of Ni-Cu-PGE sulfide ore deposit types is represented, including komatite-hosted Ni-Cu-PGE deposits; tholeiitic intrusion-hosted Ni-Cu-PGE deposits such as the Voisey’s Bay and Nebo-Babel deposits; tholeiitic high-Mg basalt and picrite-related deposits in the Noril’sk-Talnakh district; and PGE deposits with associated Ni-Cu sulfides and Cr mineralisation hosted by large layered mafic-ultramafic intrusions such as the Bushveld Complex. A summary of information for deposits of the tholeiitic intrusion-hosted type of Ni-Cu-PGE sulfide deposits, the focus of the current study, is presented in Table 2.1.

![Figure 2.1 Model of Ni-Cu-PGE sulfide ore-forming systems, based on a synthesis of information from studies of nickel sulfide deposits globally. SCLM A (depleted) and SCLM B (depleted) represent separate blocks of sub-continental lithospheric depleted mantle. See text and Table 2.1 for references.](image-url)
<table>
<thead>
<tr>
<th>Deposit</th>
<th>Mineralisation</th>
<th>Province, country</th>
<th>Magmatic event &amp; age</th>
<th>Large Igneous Province (LIP)</th>
<th>Tectonic architecture and emplacement depth</th>
<th>Parental magma</th>
<th>Sulfur saturation processes</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voisey’s Bay</td>
<td>Ni-Cu; massive &amp; disseminated sulfides; low PGE</td>
<td>Nain Plutonic Suite (NPS), Labrador, Canada</td>
<td>NPS, ~1340 Ma; &lt;5% mafic; anorthosite and granite common</td>
<td>Presence of LIP is unclear (NPS covers 19,000km²)</td>
<td>1.86-1.74 Ga “suture” (Torngat Orogen) between Archean Nain and Paleoproterozoic Churchill provs; E-W cross-structures controlled host intrusion; sulfides in ‘feeders’ and at entry to funnel-shaped intrusion; mid-crustal depth</td>
<td>High-Al basalt</td>
<td>Early sulfur saturation due to orthogneiss assimilation, causing low PGE; then S-rich paragneiss assimilation and Ni-Cu-sulfide formation</td>
<td>Lightfoot et al. (2012); Scoates &amp; Mitchell (2000)</td>
</tr>
<tr>
<td>Duluth</td>
<td>Sub-economic; disseminated Cu-Ni sulfides; low PGE?</td>
<td>Mid-Continent Rift in Superior Province, USA</td>
<td>Duluth Complex; ~1100 Ma</td>
<td>Keweenawan LIP</td>
<td>Rift within or near margin of Superior Province; large mafic intrusion intruding metasediments; upper crustal depth with co-magmatic volcanics</td>
<td>High-Al olivine tholeiite</td>
<td>Local assimilation of S-bearing sedimentary host rocks</td>
<td>Chalokwu et al. (1993); Ripley et al. (1998);</td>
</tr>
<tr>
<td>Noril’sk-Talnakh</td>
<td>Ni-Cu-PGE; massive &amp; disseminated sulfides</td>
<td>Siberian Craton, Russia</td>
<td>Siberian Traps; ~250 Ma</td>
<td>Siberian Traps LIP</td>
<td>(Failed) rifted margin of Siberian Craton and Proterozoic province; sulfide ores in sills beneath flood basalts; upper crustal depth with co-magmatic volcanics</td>
<td>Tholeitic picrite</td>
<td>Shallow crustal assimilation of S-bearing evaporites (and coal?) in host basin; chalcophile-element depletion in volcanic rocks</td>
<td>Naldrett (2004); Arndt et al. (2005)</td>
</tr>
<tr>
<td>Jinchuan</td>
<td>Ni-Cu; low PGE</td>
<td>Longshoushan Terrane, at SW margin of North China Craton</td>
<td>small intrusions along belt; ~832 Ma</td>
<td>Gubei LIP</td>
<td>At SW margin of North China Craton; mid-crustal depth</td>
<td>High-Mg basalt or ferro-picrite</td>
<td>Assimilation of S-bearing crust</td>
<td>Chen et al. (2013); Ernst (2014)</td>
</tr>
<tr>
<td>Pechenga</td>
<td>Ni-Cu; low PGE</td>
<td>Russia</td>
<td>Pechenga; ~1970 Ma</td>
<td>Pechenga-Onega LIP</td>
<td>Paleoproterozoic rifted continental margin in Archean terrane</td>
<td>Ferro-picrite or high-Mg basalt</td>
<td>Assimilation of S-bearing crust</td>
<td>Naldrett (2004); Ernst (2014)</td>
</tr>
<tr>
<td>Nebo-Babel</td>
<td>Ni-Cu; sub-economic; PGE 0.1-0.5ppm</td>
<td>Musgrave Province, central Australia</td>
<td>Part of Giles Complex; ~1075 Ma</td>
<td>Warakurna LIP, superimposed on previously metasomatised mantle (1640 Ma?)</td>
<td>“Triple junction” between crustal elements; new seismic data show Archean boundary nearby to W; mid-crustal depth</td>
<td>Tholeitic basalt</td>
<td>Assimilation of country rock orthogneiss; no external sulfur (S-isotopes ~0 per mil)</td>
<td>Godel et al. (2011); Seat et al. (2007, 2011)</td>
</tr>
</tbody>
</table>
2.2 Fundamental processes in Ni-Cu-PGE ore formation

There are a number of important processes required for the formation of economic deposits of magmatic Ni-Cu-PGE sulfide mineralisation (e.g. Naldrett, 2004), namely: (a) sufficient levels of ore elements in the magma; (b) the ability of the magma to become S-saturated, producing immiscible sulfide liquids at a stage that facilitates interaction of these sulfide liquids with sufficient magma to scavenge economic levels of the ore elements; and (c) concentration of the sulfides to form an economic deposit. The following discussion addresses each of these processes in relation to the model and geological features shown in Figure 2.1, for magmatic Ni-Cu-PGE sulfide deposits in general. Further details of the ore-forming processes are presented for the target deposit type of this study, tholeiitic intrusion-hosted Ni-Cu-PGE sulfides, in Chapter 4.

2.2.1 Generation of ore-element-rich magma: mantle melting

Arndt et al. (2005) outlined several theoretical considerations regarding controls on the Ni-Cu-PGE contents of primary mantle melts, including the mantle composition; the pressure-temperature conditions of partial melting; and the type and extent of partial melting. In the upper mantle, most Ni is hosted by olivine, and most of the PGE content is hosted by sulfide and PGE minerals. Due to the high melting temperatures of these host minerals the release of Ni and PGE to the melt typically requires moderate to high degrees of partial melting of the mantle and/or abnormally high temperatures in the mantle. This explains why komatiites and picrites, which are generated via moderate to high degrees of partial melting of the mantle, have much higher Ni and PGE contents than MORB, OIB or some alkali basalts (Arndt et al., 2005; Barnes and Lightfoot, 2005). These basalts are normally generated at ambient mantle temperatures and/or via lower degrees of partial melting, and in many cases are S-saturated at the time of partial melting (e.g. Keays, 1995; Arndt et al., 2005).

The association of many of the major Ni-Cu-PGE sulfide deposits with komatiitic, picritic and other high-Mg magmas has long been recognised, as summarised in the compilation of parent magma compositions in Table 2.1 and Table 2.2. However, tholeiitic basalts (high-Al) have been proposed as the parental melts for the Duluth and Voisey’s Bay deposits (Chalogwu et al., 1990; Scoates and Mitchell, 2000), and the parental magma for the Nebo-Babel deposit was of tholeiitic basaltic composition, according to Godel et al. (2011). A possible linking factor between these wide ranging magma compositions may be the high volumes of melt involved. Ernst (2014) argued that the majority of magmatic Ni-Cu-PGE resources are directly related to large igneous provinces (LIPs) which are, by definition, of high magma volume.

High- and moderate-degree partial melting and abnormally high mantle temperatures are favoured in geological settings where mantle plumes impact upon relatively thin lithosphere and undergo decompressional melting (Figure 2.1). LIPs are one manifestation of this process (see Ernst, 2014 for discussion of LIP origins), and represent the transfer of energy from the mantle to the crust. Lateral transitions from thicker to thinner lithosphere may guide flow of plume material towards regions of thinner lithosphere, where more extensive partial melting may occur within the plume (Begg et al., 2010; Ernst, 2014).
Table 2.2 Parent magma compositions for igneous rocks hosting major global Ni-Cu-PGE sulfide deposits.

<table>
<thead>
<tr>
<th>Ore deposit classification of Naldrett (2004)</th>
<th>Ni-Cu (20-90% sulfide ore)</th>
<th>PGE (sulfide)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Ni (PGE-Cu) deposit or district</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kambalda, Mt Keith Perseverance Thompson, Raglan</td>
<td>Komatiite</td>
<td>Pechenga</td>
</tr>
<tr>
<td>Noril’sk-Talnakh</td>
<td>Flood basalt</td>
<td>Pechenga</td>
</tr>
<tr>
<td>Duluth</td>
<td>Flood basalt</td>
<td>Pechenga</td>
</tr>
<tr>
<td>Pechenga</td>
<td>Ferro-picrite</td>
<td>Voisey’s Bay</td>
</tr>
<tr>
<td>'HAG1'</td>
<td>Anorthosite-troctolite</td>
<td>Nebo-Babel</td>
</tr>
<tr>
<td>* (not included)</td>
<td>* (not included)</td>
<td>* (not included)</td>
</tr>
<tr>
<td>Picrite-tholeite</td>
<td>U-type (high proportion)</td>
<td></td>
</tr>
<tr>
<td>Unit name</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Many unit names of komatiites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tuklonsky</td>
<td>Calculated composition</td>
<td>NB1 dykes (most primitive found)</td>
</tr>
<tr>
<td>SiO\textsubscript{2} wt. %</td>
<td>45.1</td>
<td>48.3</td>
</tr>
<tr>
<td>MgO %</td>
<td>30.8</td>
<td>15.7</td>
</tr>
<tr>
<td>Fe\textsubscript{2}O\textsubscript{3} tot %</td>
<td>11.5</td>
<td>11.2</td>
</tr>
<tr>
<td>K\textsubscript{2}O %</td>
<td>0.01</td>
<td>0.4</td>
</tr>
<tr>
<td>Degree of partial melting</td>
<td>30-50%</td>
<td>~30%</td>
</tr>
<tr>
<td>Parent magma type</td>
<td>Komatiite</td>
<td>High-Al olivine tholeiite</td>
</tr>
</tbody>
</table>

Note: The ore deposit classification of Naldrett (2004) also includes PGE (sulfide) deposit types: tholeiite ± minor U-type (e.g., Munni Munni, Pennikat); calc-alkaline type (e.g., Volkovsky-Ural Mountains); ultramafic Ural-Alaskan type e.g., Soleviev-Urals); and alkaline mafic-ultramafic type (e.g., Guli intrusion, Siberia).

* The Nebo-Babel deposit was not included in the classification of Naldrett (2004).

Other comments:
- Noril’sk: Parent magmas are relatively uncontaminated by granitic crust (although other picrite magmas are more contaminated).
- Duluth: Early high-Mg basalt in Keweenawan flows.
- Pechenga: Ferro-picritic compositions of co-genetic intrusives and extrusives; ferro-picrites not co-genetic with associated tholeiites (different mantle source); distinctive geochemistry: high MgO, FeO, TiO\textsubscript{2}, Ni, Cr, elevated incompatibles; low Al\textsubscript{2}O\textsubscript{3} (6.5-8%), fractionated REEs.
- Voisey’s Bay: Very low PGE and Au parent magmas in all of Nain Plutonic Suite; high-Al basalt from low-degree melting of source then significant fractionation and 2-stage assimilation; host is troctolite, within anorthosite province.
- Nebo-Babel: Mixed low-Ti and high-Ti basaltic magmas; low-Ti basalts (NB1) modelled as 5-10% melting of spinel-bearing source at ~60km depth in metasomatised SCLM with 0.5% H\textsubscript{2}O. Mixed melts were then contaminated by up to 30% lower crustal material; gabbronorite host.
- Jinchuan: Host is ultramafic peridotite cumulate (dunite).
Major trans-crustal to trans-lithospheric weaknesses at the margins of cratons may facilitate transfer of melt from mantle into the crust. These sites of large-volume magma production under thinner lithosphere near the margins of cratonic roots are a favourable setting for Ni-PGE-Cu sulfide deposit formation (Begg et al., 2010; Ernst, 2014). In exploration targeting it is therefore important to recognise and map the boundaries of lithospheric blocks (i.e. lithospheric architecture) not only as they exist at present but crucially at the times of mafic-ultramafic magmatism and ore formation. It is for these reasons that mapping of lithospheric architecture of the Australian continent has been incorporated into the present study of Ni-Cu-PGE sulfide mineral potential, as described in later sections of this report.

The role of melts derived from metasomatised lithospheric mantle (as compared with asthenospheric melts) in ore genesis is controversial. Some proponents advocate an important role in Ni-PGE-Cu sulfide deposit formation (e.g. Griffin et al., 2013) whereas others argue that lithospheric melts are unnecessary, notwithstanding their likely contributions in some systems such as the Bushveld Complex (e.g. Arndt, 2013). Our model, therefore, includes the possibility of melts derived from metasomatised lithospheric mantle as well as asthenospheric melts (Figure 2.1).

Higher mantle temperatures inferred during the Archean are generally thought to have been a factor in the greater abundance of komatiites and komatiite-hosted Ni sulfide deposits in the Archean and Paleoproterozoic as compared with later time periods (Figure 2.1, right-hand panel; Kerrich et al., 2005; Herzberg et al., 2007). Hoatson et al. (2006) noted an empirical association in the Yilgarn Craton between the distribution of komatiitic nickel sulfide resources and greenstone belts containing Al-undepleted ($Al_2O_3/TiO_2 = 15-25$) versus Al-depleted komatiites. Greenstone belts with Al-depleted komatiites, with or without Al-undepleted komatiites, tend to be less endowed with Ni sulfide deposits than belts dominated by Al-undepleted komatiites, suggesting an underlying magma-compositional control on the genesis and location of these deposits (J. Claoué-Long, pers. comm., 2013). The reasons for these relationships are not well understood and deserve more research. In Figure 2.1 a shallower source of Al-undepleted komatiites is shown as compared to Al-depleted komatiites which may be sourced from depths where garnet is stable (Cassidy et al., 2005).

Figure 2.1 illustrates the emplacement of mantle-derived melts at several levels in the upper lithosphere: at or beneath the base of the crust as ‘underplated material’; at mid-crustal levels; and in sub-volcanic to volcanic environments. The levels of emplacement are partly controlled by density differences between magma and host rock, among other factors, resulting in ‘stalling’ and ponding of magmas at major changes in host-rock density (e.g., the Moho, and at transitions from dense lower crust to less dense upper crust). We propose that large volumes of mafic-ultramafic igneous rock within the crust and at the Moho may represent the deeper roots of mafic-ultramafic magmatic systems which are potentially related to Ni-Cu-PGE sulfide mineral systems. These large volumes effectively represent large ‘footprints’ of the orthomagmatic mineral systems, above which the host igneous complexes may have developed. For this reason we have attempted to recognise and map such accumulations of mafic-ultramafic material using geophysical data, as described in later sections.

2.2.2 Sulfur saturation and ore-element concentration

Ni-Cu-PGE sulfide ore formation occurs in mid- to upper-crustal magma chambers following the interaction of the parent mantle melts or their fractionated products with crustal rocks, inducing sulfur saturation. Sulfide liquid separation (immiscibility) occurs where the solubility limit of sulfur in the silicate-rich magma is attained, which is controlled principally by temperature, pressure and magma...
composition. In general, sulfur solubility in basaltic to komatiitic melts increases with increasing temperature, $a_{FeO}$ and $f_{S2}$, and decreases with increasing pressure, $f_{CO2}$, $a_{SO2}$ and $a_{Na2O}$ (see Naldrett, 2004; Arndt, 2005; and references therein). This means that at any particular depth and temperature the solubility of sulfur in a komatiitic melt will be higher than that in a basaltic magma, but in both cases the sulfur solubility increases in the magmas as they ascend through the mantle and crust because the effect of decreasing pressure dominates over the effect of decreasing temperature. For typical upper mantle sulfur contents (~250 ± 50 ppm S, McDonough and Sun, 1995) this results in moderate to very high degrees of sulfur under-saturation of the melts when they reach mid- or upper-crustal settings. Most (closed-system) picritic to komatiitic magmas with typical upper mantle sulfur contents will become saturated in sulfur only relatively late in their fractional crystallisation evolution and as temperature declines (e.g., Ripley and Li, 2013).

Chalcophile elements, such as the PGE, Au and Cu, as well as the chalcophile-siderophile element Ni, present in the melt at this late stage will be strongly partitioned into sulfide phases. However, two factors make late-stage sulfur saturation unfavourable for the formation of Ni sulfide ore deposits. First, most Ni already will have been sequestered into early-crystallised olivine, where magmas crystallise abundant olivine. Second, sulfur saturation of melt with typical upper mantle sulfur contents of ~250 ± 50 ppm will yield relatively small volumes of immiscible sulfide liquid, which would require extremely efficient concentration processes to form large volumes of ore-grade Ni sulfides (Ripley and Li, 2013).

Due to the fundamental factors outlined above, the formation of nickel sulfide ores is favoured (but does not exclusively occur) in geological environments where sulfur has been added to Ni-bearing magmas. Sulfur addition can be achieved via assimilation of sulfide or sulfate mineral-rich wall rock. This is evident from sulfur isotope compositions of magmatic sulfides in nickel sulfide deposits which show shifts from mantle values towards those of sulfide/sulfate minerals in the wall rocks (see Barnes and Lightfoot, 2005). Ore-bearing igneous rocks also commonly show other isotopic and chemical evidence of contamination by crustal rocks (e.g., Lesher and Arndt, 1995; Naldrett, 2004 and references therein). Assimilation of silica-rich material or mixing with relatively silicic melts also may induce sulfur saturation in the absence of externally-derived sulfur, as suggested for the formation of the Nebo-Babel Ni sulfide deposits in Western Australia (Seat et al., 2009; Godel et al., 2011; Ripley and Li, 2013). Large sulfide deposits formed through this process may be very rare due to the extreme concentration factors required to accumulate sufficient volumes of sulfide liquids in such systems where external sulfur appears not to have been added.

The fundamental processes of generation of Ni-Cu-PGE-bearing magmas are similar for tholeiitic intrusion-related, picrite-related, and komatiite-related deposits, as described by Begg et al. (2010) and summarised above. Different deposit types and sub-types develop where the differing parental magmas attain sulfur saturation in varying geological settings and by different mechanisms. For example, komatiitic nickel sulfide deposits form where lavas or subvolcanic intrusions acquire sulfur from supracrustal host rocks close to the site of emplacement of the komatiites, resulting in volcanic- or sub-volcanic hosted massive sulfides (e.g., Lesher and Groves, 1986). The magma systems hosting the giant Noril’sk Ni-PGE-Cu deposits locally attained sulfur saturation within sub-volcanic sill complexes via assimilation of sulfur from sulfate-bearing sedimentary basin rocks (Naldrett, 2004; Barnes and Lightfoot, 2005). The co-magmatic flood basalts do not host the Noril’sk orebodies. Parental magmas for the Voisey’s Bay deposit most likely were sulfur-saturated in the mantle source region, resulting in low PGE contents in the Nain Plutonic Complex, but this process did not remove significant Ni from the melt (Lightfoot et al., 2012). A second stage of sulfur saturation occurred within mid-crustal magma chambers via crustal contamination, resulting in separation and concentration of
immiscible sulfide liquid containing high concentrations of Ni (Scoates and Mitchell, 2000; Lightfoot et al., 2012). The geological environments, ore body morphologies and textures vary greatly between these example deposit types and yet there are shared fundamental lithospheric scale controls and processes of magma generation and sulfide formation.

The formation of the nickel sulfide ores, whether in tholeiitic intrusions or picritic to komatiitic magmas, requires sulfur saturation before major crystallisation of olivine which would otherwise sequester much of the available Ni in the melt. These sulfides may contain moderate PGE abundances. In contrast, high-grade PGE ores in mafic-ultramafic magmatic systems form where sulfur saturation is attained relatively late in the crystallisation history of the host magmatic system, under conditions where the PGE may be scavenged from very large volumes of magma to produce high-tenor PGE-rich sulfide segregations. These conditions appear to be optimally met within large layered mafic-ultramafic intrusions such as the Bushveld Complex. Much smaller, less endowed, examples in Australia include the Archean Munni Munni intrusion in the Pilbara Craton of Western Australia (Hoatson et al., 2006, and references therein).
3 Prospectivity analysis method

3.1 Mineral systems framework

This study of Australia’s potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits applies a mineral systems approach (Wyborn et al., 1994) to highlight broad regions of the continent that may have high potential for discovery of major deposits. Geoscience Australia and its predecessors developed and have utilised the mineral systems concept, which has been modified subsequently for different purposes in the mineral exploration and research communities (e.g., Walshe et al., 2005; McCuaig et al., 2010; Hagemann et al., 2015). The original mineral systems concept of Wyborn et al. (1994) included seven important geological factors that were considered important in defining any mineralising system: (1) sources of mineralising fluids and ligands, (2) sources of metals and other ore-forming constituents, (3) fluid migration pathways, (4) thermal gradient, (5) energy source, (6) a mechanical and structural focusing mechanism at the ore deposition site, and (7) chemical and/or physical traps for ore precipitation. Wyborn et al. (1994) introduced the concept of ‘essential ingredients’ and ‘mappable criteria in applying the mineral systems concept, and emphasised that the total size of the systems of fluid-rock interaction are generally much larger than the ore deposits themselves. Thus, the mapping and identification of district- to regional-scale ‘footprints’ of mineral systems can provide a much larger target for mineral exploration than the deposits themselves. This concept has underpinned a series of subsequent studies of mineral potential by Geoscience Australia and by the Centre for Exploration Targeting at the University of Western Australia. Geoscience Australia has applied a modified version of the mineral systems approach in which the concept of a critical time window of ore formation has been emphasised, and the seven factors of Wyborn et al. (1994) have been condensed into four components of mineral systems that can be mapped at district, regional and continental scales (Skirrow, 2009; Huston and van der Wielen, 2011). These four components are illustrated schematically in Figure 3.1 and comprise:

- energy sources or drivers of the ore-forming system;
- crustal and mantle lithospheric architecture;
- sources of ore constituents, and
- gradients in ore depositional physico-chemical parameters.

Although the original mineral systems concept was developed for hydrothermal ore-forming systems, it can also be applied to orthomagmatic mineral systems, as in the assessments of mineral potential of Proterozoic mafic-ultramafic intrusions in the Arunta region (Miezitis et al., 2006) and in a study of magmatic Ni sulfide potential of the Yilgarn Craton (Porwal et al., 2010).

As this study has been undertaken at a continental-scale to identify regions of high potential for intrusion-hosted Ni-Cu-PGE mineralisation, the methodology has been modified to focus on geological, geophysical and geochemical features mappable at the national- to regional-scale rather than those mappable at the deposit scale.
3.2 Prospectivity modelling approach and GIS methods

Mineral deposits form as a result of the coincidence in time and space of favourable geological conditions. At its most basic level, a prospectivity analysis study seeks to identify and map relevant geological evidence to determine the locations (in both 3D space and time) with greatest potential for previously unrecognised mineralisation. It is assumed in prospectivity modelling that (1) a specific location is prospective if it is characterised by the same or similar evidential features as those of known mineral deposits of the type sought, and (2) if evidential features are present in one location and not another then the former has higher prospectivity than the latter (Carranza, 2009).

Two broad categories of methods have been employed in prospectivity analyses: data-driven and knowledge-driven (Bonham-Carter, 1994; Knox-Robinson and Wyborn, 1997; Carranza, 2009). Data-driven prospectivity analysis methodologies utilise GIS software and digital spatial data and are typically applied in study areas where there are numerous known deposits. Data-driven analyses build upon the spatial relationships between known mineral deposits or occurrences (training data) and specific geological and/or geophysical features represented in the digital spatial datasets. These statistical relationships are then utilised in automated modelling of the mineral potential in areas distal from the known deposits. The statistical methods in data-driven assessments include logistical regression, weights-of-evidence and neural networks (Bonham-Carter, 1994; Porwal and Kreuzer, 2010).

Knowledge-driven or qualitative empirical prospectivity modelling methods differ from data-driven analyses by utilising conceptual models of ore formation (e.g., mineral systems model). Generally the work flow involves: (1) identification of critical geological processes of ore formation, (2) identification of the features in the geological record that are the product of the critical processes and which are mappable, (3) selection and compilation of digital spatial data best representing the mappable features, and (4) application of these features in the prospectivity modelling procedure (Carranza, 2009).
Potential for intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia

geological features, (4) subjective assignment of weightings or prospectivity values to the constituent map datasets, and (5) generation of the overall prospectivity maps by combining the input spatial data layers. In GIS-assisted ‘manual’ assessments step (3) may simply involve the selection of an entire geological region or map unit that is then attributed with values of prospectivity. These have been carried out at regional scales, for example by Miezitis et al. (2006), González-Álvarez et al. (2010) and Joly et al. (2012), and at national scale by Geoscience Australia prior to 2006 (www.australianminesatlas.gov.au) and Kreuzer et al. (2010). Alternatively, steps (3) and (4) may involve generation of digital maps (vector or raster) with varying fuzzy logic-based values across the ‘predictor’ maps. Examples of regional studies in Australia using this approach include: Huston (2009); Czarnota et al. (2010), González-Álvarez et al. (2010), Huston and van der Wielen (2011), Schofield at al. (2012), Joly et al. (2012), and Occhipinti et al. (2015). It is this latter method of GIS-based knowledge-driven analysis using overlay of fuzzy-attributed predictor maps that has been employed in the current study, for the following reasons.

Although data-driven prospectivity modelling methods are more objective than knowledge-driven methods the former are less effective in regions where there are few or no known mineral deposits that could be used as training data. The objective of the present study is to identify unrecognised prospectivity in ‘greenfields’ regions of Australia, for which a mineral systems-based knowledge-driven modelling approach is considered the most appropriate method. The availability of a series of new continental-scale digital geological, geochemical and geophysical datasets now allows improved spatial resolution of analysis and a more comprehensive assessment of the continental-scale spatial and temporal controls on Ni-Cu-PGE sulfide ore formation. Nevertheless, it is recognised that the selected formulation of the conceptual model of ore formation will inevitably result in biases in the results. It is for this reason that the constituent input datasets have been made available separately so that users may use these data for their own purposes.

A further and significant bias of the prospectivity study arises from the heterogeneity of data coverage across the continent for some of the input datasets. For example, datasets derived from whole-rock geochemical analyses from the OZCHEM database tend to be clustered in well-studied and outcropping regions of Australia. Several techniques have been employed to minimise the spatial bias introduced by such heterogeneity of data coverage, including weighting techniques as explained further below. We argue that despite these limitations the approach used in the study enables identification of several previously unrecognised regions of mineral potential as well as identifying known regions, and is therefore useful as a first attempt at mapping prospectivity at continental scale. Improved data coverage at higher density may yield additional areas of mineral potential in future.

This study is, to our knowledge, the first published continental-scale assessment of mineral potential of Australia that applies a mineral systems-based knowledge-driven approach together with GIS techniques to integrate fuzzy logic-based predictor maps. The study also uses a wider range of geological, geophysical and geochemical datasets as inputs than in most previous prospectivity studies in Australia.

3.3 Theoretical and mappable criteria and weightings

Using the mineral systems framework, ‘theoretical’ conceptual criteria were developed for each of the four key components of the mineral system (sources, architecture, energy and ore depositional gradients) that reflect the geological processes perceived to be essential in ore formation. These processes generally are not observable directly for the fossil mineral systems being investigated, and
so for the purposes of spatial modelling each theoretical criterion was ‘translated’ into one or more observable and mappable geological features (mappable criteria). The digital geoscientific datasets best representing these features were then identified and compiled as spatial datasets in a GIS. The resultant maps are termed ‘predictor maps’ by some workers (see Carranza, 2009). Weightings were then assigned to each of the raster maps of the input datasets (see below). In the final steps the maps were combined in the GIS by overlaying the weighted rasters, first for each of the four mineral system components and then integrated into a final mineral potential map. This work flow using the mineral systems approach is illustrated in Figure 3.2, and further technical details are presented in Appendix A.

The assignment of weightings to the input datasets is a key part of the mineral potential modelling work flow. For each input dataset weighting values between [0] and [1] (similar to fuzzy logic membership) were assigned subjectively by the authors, using the definitions of certainty of Meyer and Brooker (1991) as a guide (Table 3.1), for each of the following three factors:

- Importance (I) – reflects the overall importance of the theoretical criterion to the mineral system;
- Applicability (A) – reflects the certainty that the mappable geological proxy reflects the desired process given by the theoretical criterion; and
- Confidence (C) – reflects the confidence in the data source, both in terms of spatial accuracy and overall data quality.

Table 3.1 Guide for assigning importance, applicability and confidence values, together with definitions of certainty modified from the Sherman-Kent Scale (see Meyer and Brooker, 1991).

<table>
<thead>
<tr>
<th>Numerical value</th>
<th>Value description</th>
<th>Definition (confidence of value description being true)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Total or critical</td>
<td>Proven or definitely true</td>
</tr>
<tr>
<td>0.9</td>
<td>Extremely high</td>
<td>Virtually certain or convinced</td>
</tr>
<tr>
<td>0.8</td>
<td>Very high</td>
<td>Highly likely</td>
</tr>
<tr>
<td>0.7</td>
<td>High</td>
<td>Likely</td>
</tr>
<tr>
<td>0.6</td>
<td>Moderately high</td>
<td>Slightly higher than even chance</td>
</tr>
<tr>
<td>0.5</td>
<td>Moderate</td>
<td>Even chance</td>
</tr>
<tr>
<td>0.4</td>
<td>Moderately low</td>
<td>Slightly lower than even chance</td>
</tr>
<tr>
<td>0.3</td>
<td>Low</td>
<td>Unlikely</td>
</tr>
<tr>
<td>0.2</td>
<td>Very low</td>
<td>Could be possible, but probably not</td>
</tr>
<tr>
<td>0.1</td>
<td>Extremely low</td>
<td>Possible but very doubtful</td>
</tr>
<tr>
<td>0</td>
<td>Nil</td>
<td>Proven untrue or impossible</td>
</tr>
</tbody>
</table>

- The three weighting values of ‘I’, ‘A’ and ‘C’ for each dataset were then multiplied to yield an overall weighting value for that dataset. Multiplication of this overall weighting by the normalised values (maximum 1000) of the input raster for the particular dataset results in a predictor map showing spatial variations in fuzzy logic membership values. Some datasets such as point and line data required assignment of buffers, which were treated by attributing the buffered zones with higher weightings than the unbuffered zones.
In general terms this knowledge-driven approach is similar to that described by McCuaig et al. (2010), and applied by Occhipinti et al. (2015), involving the combination of fuzzy logic and index overlay methods (Bonham-Carter, 1994). However, in the present study we have taken the additional step of creating an intermediate series of maps representing the contributions of each of the four mineral systems components, with raster values normalised to a maximum fuzzy membership value of 1 (Figure 3.2). In combining these four maps into the final mineral potential map the four components are therefore permitted to contribute equally, reflecting the assumption in this study that all four components must have been present in time and space for the mineral system to have formed a major ore deposit. This mitigates against the possible distortion of prospectivity results in the case where more input datasets have been used to generate one of the mineral system components than for another component with fewer input datasets.

The theoretical and mappable criteria and weightings for modelling the potential for tholeiitic intrusion-hosted nickel sulfide deposits in Australia are given in Table 3.2, and are discussed in detail in the next sections as well as in Appendix A.
Figure 3.2 Diagram illustrating generalised workflow for mineral potential modelling in the present study, using a mineral systems framework.

<table>
<thead>
<tr>
<th>Mineral system component</th>
<th>Theoretical criteria</th>
<th>Mappable criteria</th>
<th>Datasets (weighted)</th>
<th>Normalised maps of components</th>
<th>Mineral potential map</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver / energy sources</td>
<td>process A</td>
<td>geological feature X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>process B</td>
<td>geophysical feature Y</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Architecture</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Sources of ore metals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Ore depositional gradients</td>
<td></td>
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<tr>
<td>Mineral system component</td>
<td>Theoretical criteria</td>
<td>Mappable criteria</td>
<td>Datasets</td>
<td>Weightings</td>
<td>Importance</td>
</tr>
<tr>
<td>--------------------------</td>
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<tr>
<td>Energy sources or drivers of the ore-forming system</td>
<td>Large-volume melting of the mantle</td>
<td>Large Igneous Provinces</td>
<td>Australian Proterozoic Large Igneous Provinces GIS Dataset (Claoué-Long et al. 2015)</td>
<td>0.8</td>
<td>0.3</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Geological unit polygons, points and lines corresponding to each Proterozoic LIP. The Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Crustal and mantle lithospheric architecture</td>
<td>Magma pathways through the lithosphere</td>
<td>Boundaries of lithospheric blocks</td>
<td>Australian Seismological Reference Model AuSREM (Kennett et al., 2013a); horizontal gradients in $V_{sv}$</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Major crustal domain boundaries</td>
<td>Major Crustal Boundaries of Australia based on seismic reflection data (Korsch and Doublier, 2014); 50 km buffer</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Isotopic Domain Boundaries of Australia (Champion, 2015) interpreted from Nd model age data; 25 km buffer</td>
<td>0.6</td>
<td>0.5</td>
</tr>
</tbody>
</table>
## Mineral system component

### Sources of ore metals: Ni, Cu, PGE

<table>
<thead>
<tr>
<th>Theoretical criteria</th>
<th>Mappable criteria</th>
<th>Datasets</th>
<th>Weightings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate to high degrees of partial melting to release nickel from olivine (and PGEs from host minerals)</td>
<td>Geological unit polygons, points and lines with “ultramafic” or “ultramafic-mafic” in the <code>bulkComposition</code> field</td>
<td>The Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
<td>0.8</td>
</tr>
<tr>
<td>Geological unit polygons, points and lines with “mafic-ultramafic” in the <code>bulkComposition</code> field</td>
<td>The Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Geological units and events with ≥12% MgO</td>
<td>OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Tholeiitic composition of magmas</td>
<td>Mafic rocks classified as tholeiitic</td>
<td>OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
<td>0.8</td>
</tr>
<tr>
<td>High chalcophile-element abundances (Ni, PGE, Cu)</td>
<td>High Ni (95th percentile)</td>
<td>OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014); Ni+Cu+PGE combined into single dataset</td>
<td>0.7</td>
</tr>
<tr>
<td>High Cu Cu ≥ 180 ppm (90th percentile)</td>
<td></td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>High PGE Pt ≥ 10 ppb or Pd ≥ 10 ppb</td>
<td></td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>Mineral system component</td>
<td>Theoretical criteria</td>
<td>Mappable criteria</td>
<td>Datasets</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------------------</td>
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<td>--------------------------------------------------------------------------</td>
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<tr>
<td></td>
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<tr>
<td>Ore depositional gradients</td>
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</tr>
</tbody>
</table>

*Vp = P-wave velocity; *Vsv = vertical component of shear-wave velocity
4 Tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineral systems

Below we describe the theoretical and mappable criteria that have been developed from the conceptual model (Chapter 1) for each of the mineral systems components outlined in Table 3.2.

4.1 Mineral system component: energy sources

4.1.1 Introduction

For the sources of energy component of the mineral system a single theoretical criterion was identified along with two mappable criteria, for which three datasets were chosen as proxies (Table 4.1).

Table 4.1 Theoretical criterion, mappable criteria and datasets for the energy sources in tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineral systems. Extract from Table 3.2.

<table>
<thead>
<tr>
<th>Mineral system component</th>
<th>Theoretical criterion</th>
<th>Mappable criteria</th>
<th>Dataset(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy sources or drivers of the ore-forming system</td>
<td>Large-volume melting of the mantle</td>
<td>Large Igneous Provinces</td>
<td>Australian Proterozoic Large Igneous Provinces GIS Dataset (Claué-Long et al. 2015)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Geological unit polygons, points and lines corresponding to each Proterozoic LIP. The Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
</tr>
<tr>
<td></td>
<td>Thickness of inferred mafic rocks in crust</td>
<td></td>
<td>Australian Seismological Reference Model AuSREM (Salmon et al. 2013); *Vp &gt; 7.1 km/s above the Moho</td>
</tr>
</tbody>
</table>

*Vp = P-wave seismic velocity

4.1.2 Theoretical criterion: large-volume melting of the mantle

Parental melts for nickel sulfide deposits are generated by 20–50% partial melting of a mantle source (Keays, 1995; Arndt et al., 2005; Zhang et al., 2008). Figure 4.1a shows that at an ambient mantle potential temperature of ~1300°C no melting will occur beneath lithosphere thicker than ~50 km; a 20% melt fraction can only be achieved if the top of the melting column is at the Earth’s surface. In order to achieve higher melt fractions and generate melt beneath continent where the lithosphere is more than 50 km thick elevated mantle potential temperatures are necessary, either through secular changes (e.g. higher ambient temperatures in the past) and/or via convective upwelling (e.g. mantle plumes). For example, with mantle potential temperatures of ~1500°C (such as may have been present in the ambient Archean mantle; Pollack, 1997), melting can occur at greater depths, with 20% partial melting achievable at depths of 50 km. Similarly, petrological and geophysical studies show that mantle potential temperatures in plumes can exceed the ambient mantle temperature by up to 200–300°C (McKenzie and O’Nions, 1991; Nisbet et al., 1993; Herzberg et al., 2007). Notwithstanding these elevated mantle temperatures thinner lithosphere facilitates higher degrees of partial melting.
and the development of thick melt columns (Figure 4.1b). It is this geological setting that is highly favourable for generation of large volumes of mantle melt.

Large Igneous Provinces (LIPs) are widely believed to result from the ascent of mantle plumes from the deep mantle (e.g., Morgan, 1971; Coffin and Eldholm, 1994; Ernst, 2014). Although a mantle-plume origin is most compelling according to Ernst (2014), several alternative processes have been proposed, including: lithospheric delamination, decompression melting during rifting including back-arc settings, sublithospheric convection, impact-induced decompression melting, edge-driven convection, and various plate tectonic-related processes (see review by Ernst, 2014). LIPs are defined as mainly mafic (±ultramafic) magmatic provinces with aerial extents >0.1 million km² and igneous volumes > 0.1 million km³, with intraplate tectonic settings or chemical affinities, and are emplaced during a short pulse or multiple pulses (less than 1-5 m.y.) with a maximum duration of < 50 m.y. (Bryan and Ernst, 2008; Ernst, 2014). Therefore, identification of LIPs in the geological record may indicate the impact of a plume on the lithosphere.

LIPs occur in both continental and oceanic intraplate settings, as continental flood basalts, ocean basin flood basalt, layered mafic-ultramafic intrusions, sill complexes and dyke swarms (Bryan and Ernst, 2008). There is a strong association between magmatic Ni-Cu-PGE mineralisation and the presence of LIPs (e.g., Naldrett, 1997). For example, there are a number of world-class magmatic Ni-Cu-PGE deposits associated with LIPs: the magmatic Ni-Cu-PGE mineralisation in the Noril’isk-Talnakh district is associated with the Permian Siberian Traps LIP (Naldrett et al., 1992); and the mineralisation in the Duluth Complex formed as part of the Keweenawan LIP (Miller and Ripley, 1996; Table 2.1).
4.1.2.1 Mappable criterion and datasets: Large Igneous Provinces (LIPs)

Nineteen LIPs have been proposed in Australia, ranging in age from Archean to Recent (Table 4.2). Determination of the original volume and extent of igneous events is fraught with the problem of variable preservation. LIPs, especially pre-Phanerozoic LIPs, may be identifiable only from scattered remnants, such as dyke swarms and sills (Pirajno and Hoatson, 2012). Therefore, many of the LIPs in Australia have been proposed based on time-equivalence of the igneous rocks (supported by geochronological data), supported in only a few cases by geochemical data indicating co-magmatism of the separated occurrences (e.g., Glass and Phillips, 2006).

In this nickel sulfide prospectivity study we have used the extent of the following large igneous provinces to create input layers: ~1780 Ma Hart LIP, ~1210 Ma Marnda Moom LIP, ~1070 Ma Warakurna LIP, ~825 Ma Gairdner LIP, and ~510 Ma Kalkarindji LIP (Figure 4.2). These LIPs were chosen because their time-space distributions are available from the Australian Proterozoic Large Igneous Provinces GIS Dataset (Claoué-Long et al., 2015), as described by Claoué-Long and Hoatson (2009). Digital spatial data for the remaining LIPS are not yet available in convenient formats. Even among the five chosen LIPs, however, it should be noted that only the youngest two of these LIPs (Gairdner and Kalkarindji) are established as comagmatic provinces based on both time correlation and geochemical equivalence.

Two GIS datasets (layers) have been created to represent these LIPs in space. The first layer contains all known volcanics, dykes and sills that correspond to each LIP, as recorded in the Australian Mafic Ultramafic Magmatic Events GIS Dataset (Thorne et al., 2014), compiled from solid geology or surface geology maps of Australia. The solid geology data were available mainly for the western two-thirds of the continent, corresponding generally to Precambrian basement provinces. No consistent solid geology datasets for mafic and ultramafic rocks were available for the Phanerozoic of eastern Australia, and so the Australian Mafic-Ultramafic Magmatic Events GIS Dataset utilised the surface geological extents for this part of the continent. Summaries of some of the data are shown in Figure 1.4, Figure 1.5 and Figure 1.6.

The second dataset layer has been produced using the Australian Proterozoic Large Igneous Provinces GIS Dataset (Claoué-Long et al., 2015), which is an interpreted extent of each of the five selected LIPs created using the known geology and geochronology as well as igneous province boundaries from the map of Australian Crustal Elements (Shaw et al., 1996).

The first layer, created from known geological information, was given a higher weighting (more confidence) in the analysis than the second layer.
Table 4.2 List of Large Igneous Provinces located in Australia. Modified from Pirajno and Hoatson (2012) and Ernst (2014).

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>Large Igneous Province Name</th>
<th>Location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2920</td>
<td>Munni Munni</td>
<td>Pilbara Craton</td>
<td>Hoatson et al., 2006; Pirajno and Hoatson, 2012</td>
</tr>
<tr>
<td>2770</td>
<td>Fortescue</td>
<td>Pilbara Craton</td>
<td>Blake et al., 2004</td>
</tr>
<tr>
<td>2700</td>
<td>Eastern Goldfields</td>
<td>Yilgarn Craton</td>
<td>Barnes et al., 2012; Said et al., 2012.</td>
</tr>
<tr>
<td>2420</td>
<td>Widgiemooltha</td>
<td>Yilgarn Craton</td>
<td>Smirnov et al., 2013</td>
</tr>
<tr>
<td>1830-1790</td>
<td>Hart</td>
<td>North Australia</td>
<td>Page and Hoatson, 2000; Pirajno and Hoatson, 2012</td>
</tr>
<tr>
<td>1790-1760</td>
<td>Eastern Creek</td>
<td>North Australia</td>
<td>Pirajno and Hoatson, 2012</td>
</tr>
<tr>
<td>1690-1670</td>
<td>Willyama</td>
<td>South Australia</td>
<td>Gibson et al., 2004; Pirajno and Hoatson, 2012</td>
</tr>
<tr>
<td>1590</td>
<td>Gawler Range</td>
<td>South Australia</td>
<td>Daly et al., 1998; Budd et al., 2001; Pirajno and Hoatson, 2012</td>
</tr>
<tr>
<td>1320</td>
<td>Derim-Derim</td>
<td>North Australia</td>
<td>Pirajno and Hoatson, 2012</td>
</tr>
<tr>
<td>1210</td>
<td>Marnda Moorn</td>
<td>Yilgarn Craton</td>
<td>Pirajno and Hoatson, 2012</td>
</tr>
<tr>
<td>1070</td>
<td>Warakurna</td>
<td>West-central Australia</td>
<td>Wingate et al., 2004; Pirajno and Hoatson, 2012</td>
</tr>
<tr>
<td>825</td>
<td>Gairdner</td>
<td>Australia</td>
<td>Zhao et al., 1994; Ernst et al., 2008</td>
</tr>
<tr>
<td>180</td>
<td>Boucaut</td>
<td>Adelaide Geosyncline</td>
<td>Ernst et al., 2008</td>
</tr>
<tr>
<td>760</td>
<td>Mundine Well</td>
<td>Pilbara and Yilgarn Craton</td>
<td>Wingate and Giddins, 2000</td>
</tr>
<tr>
<td>510</td>
<td>Kalkarindji</td>
<td>Australia</td>
<td>Glass and Phillips, 2006; Pirajno and Hoatson, 2012</td>
</tr>
<tr>
<td>180</td>
<td>Karoo-Ferrar-Tasman</td>
<td>Tasmania</td>
<td>Storey and Kyle, 1997; Pirajno and Hoatson, 2012</td>
</tr>
<tr>
<td>160-140</td>
<td>NW Australian margin</td>
<td>Northwest Australia</td>
<td>Coffin and Eldhom, 1992; Pirajno and Hoatson, 2012</td>
</tr>
<tr>
<td>130</td>
<td>Bunbury</td>
<td>Perth Basin</td>
<td>Zhu et al., 2009</td>
</tr>
<tr>
<td>120</td>
<td>Whitsunday</td>
<td>Eastern Queensland</td>
<td>Pirajno and Hoatson, 2012</td>
</tr>
</tbody>
</table>
4.1.2.2 Mappable criterion and datasets: thickness of inferred mafic rocks in the crust

Large shallow-crust and surface outpourings of mafic magma associated with LIPs are thought to represent just a fraction of the total volume of magmatism, because a large component of melt is trapped at the base of, or within, the middle to lower crust (White et al., 2008). Melt migration through the lower and middle lithosphere is thought to be a consequence of buoyancy-driven porous flow (e.g. Stolper et al., 1981; McKenzie, 1994). It follows that as the density contrast between rising mantle-derived melt and adjacent rocks approaches zero, at the base of the crust, the melt may stall or even freeze within a series of sills. There is petrological, geophysical and geomorphic evidence for this phenomenon known as mafic underplating (e.g. Cox, 1993; Brodie and White, 1994; MacLennan and Lovell, 2002; Thybo and Artemieva, 2013).
Figure 4.3 Minimum thickness of mafic material within the crust estimated by calculation of the cumulative thickness of material with P-wave velocity (Vp) values greater than 7.1 km/s above the Moho, using the Australian Seismological Reference Model (AuSREM) – Crustal Component (Salmon et al., 2013).

Regions of underplating are characterised seismically by high P-wave velocities, in the range 6.9–7.8 km/s (Thybo and Artemieva, 2013). These regions can be mapped using active-source wide-angle refraction seismic profiles or passive seismic techniques, although these datasets only provide a present-day snapshot. Accordingly, it is difficult to unequivocally link surface volcanism and an imaged underplate as the underplate may be a consequence of multiple events of which the surface expression may no longer exist, for example if it has been removed by erosion. Nevertheless, thick regions of underplating, whether a result of one or many LIP events, are an indicator of past mantle thermal anomalies. On this premise we have endeavoured to map the distribution of mafic underplating beneath the Australian continent.

Salmon et al. (2013) combined velocity profiles from historic active-source wide-angle seismic profiles and more recent passive seismic studies to construct the crustal component of the Australian Seismological Reference Earth Model (AuSREM). This model consists of a 0.5°×0.5° degree grid with a 1 km vertical resolution, from the surface to a depth of 45 km. Figure 4.3 shows the cumulative thickness of material with P-wave velocities (Vp) greater than 7.1 km/s above the Moho from the AuSREM model. This map is a proxy for the minimum total thickness of mafic rocks within the crust,
and was used in the present study of mineral potential modelling as a proxy for the sources of energy in the Ni-Cu-PGE mineral system. The majority of these putative mafic rocks occur directly above the Moho and, therefore, can be described as an underplate (Figure 4.4).

Figure 4.4 Down-to-the-north perspective view of a proxy for the minimum thickness of mafic material within the crust. Black line = coast line; grey surface = Moho; coloured = depth to the top of material with P-wave velocities (Vp) >7.1 km/s. The image shows that values of Vp >7.1 km/s mostly occur at depths exceeding 20 km in zones directly above the Moho rather than higher within the crust.

Figure 4.3 also shows the distribution of data points used to constrain lower crustal velocities within AuSREM. Naturally, uncertainty of velocities, and therefore the derived proxy, increases away from these data points. In order to maintain consistency between datasets the Moho model of Salmon et al. (2013) was used to pick the base of the crust (Figure 4.5). Spatially, the Moho is better constrained than the velocity model as it incorporates data from a significant number of reflection seismic profiles. Beneath reflection seismic traverses the depth uncertainty of the Moho is ± 2 km, which arises from the application of a constant velocity model to convert depths measured in two-way travel times on reflection seismic profiles to depths in kilometres.
Figure 4.5 Moho depth from the AuSREM seismic tomography dataset (Salmon et al., 2013).
### 4.1.3 Results for mineral system component: energy sources

The three datasets described above were weighted with the values from Table 3.2. These were then summed, by overlaying the rasters, to yield a map of fuzzy membership values of the energy sources component of the mineral system, shown in Figure 4.6. The map highlights a number of areas where there are high values representing the energy source component, including the Gairdner Dyke Swarm in South Australia, the Giles Complex in the Musgrave Province, the Kulkatharra Dolerite in the Hamersley Basin and the Hart Dolerite in the Kimberley Province. Of particular note is a large area of high values to the east and southeast of the Pilbara Craton in central-northern Western Australia. Here the interpolated areal extents of four of the five large igneous provinces coincide spatially with high values in the raster of mafic thickness in the crust. Some of the smaller areas of maxima are outlined by solid geology polygons of mafic or ultramafic members of the LIPs, because these polygons (from Thorne et al., 2014) have high overall weighting compared to the broader polygons of the LIPs or mafic thickness in the crust datasets (Table 3.2).

![Figure 4.6 Variation in values of the energy sources component in the mineral potential modelling. High values are most favourable. This input raster contributes 25% of the final mineral potential output.](image)

Potential for intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia
4.2 Mineral system component: lithospheric architecture

4.2.1 Introduction

For the lithospheric architecture component of the mineral system a single theoretical criterion was identified along with two mappable criteria, for which three datasets were chosen as proxies (Table 4.3).

Table 4.3 Theoretical criterion, mappable criteria and datasets for the lithospheric architecture component of tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineral systems. Extract from Table 3.2.

<table>
<thead>
<tr>
<th>Mineral system component</th>
<th>Theoretical criterion</th>
<th>Mappable criteria</th>
<th>Dataset(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crustal and mantle</td>
<td>Magma pathways through the lithosphere</td>
<td>Boundaries of lithospheric blocks</td>
<td>Australian Seismological Reference Model AuSREM (Kennett et al., 2013a) and horizontal gradients in Vsv*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Major crustal domain boundaries</td>
<td>Major Crustal Boundaries of Australia based on seismic reflection data (Korsch and Doublier, 2014); 50 km buffer</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Isotopic Domain Boundaries of Australia (Champion, 2015) interpreted from Nd model age data; 25 km buffer</td>
</tr>
</tbody>
</table>

*Vsv = vertical component of the seismic shear-wave velocity

4.2.2 Theoretical criterion: magma pathways through the lithosphere

Most large magmatic nickel sulfide deposits form within rift environments, either in intracontinental settings or associated with (former) passive margins (e.g. Naldrett, 2004; Begg et al., 2010). There are no known major deposits of the type modelled in this study associated with magmatic arcs in convergent margins although rare examples of deposits hosted by rifted pre-existing island arc are known (Naldrett, 2004). These extensional environments are not surprising, given that moderate to high degrees of partial melting beneath the continents is favoured in regions of thinned lithosphere (Figure 4.1).

Empirically it is observed that many major magmatic nickel sulfide deposits are located at or near the margins of lithospheric blocks (e.g. Kerrich et al., 2005; Begg et al., 2010; Ernst, 2014). Table 2.2 and Figure 4.7 demonstrate this spatial relationship globally and in Australia. Begg et al. (2010) proposed that most major magmatic nickel sulfide deposits occur along craton margins because they are the areas of thinnest subcontinental lithospheric mantle (SCLM < 150 km thick). Because ascent of mantle-derived magma is driven by buoyancy, hot mantle material migrates into these regions of thinner lithosphere where greater degrees of decompressional melting can take place. In order to avoid early sulfur saturation of the melt it is important for parental melts to ascend into the mid- to upper-crust without significant crustal contamination. Above the brittle-ductile transition in the upper lithosphere, melt migration is aided by brittle faults and fractures. These structures facilitate rapid magma transport thereby limiting sulfur saturation at depth. These arguments stress the importance of lithospheric architecture for the localisation and formation of magmatic Ni deposits and highlight the necessity of identifying regions where thinned continental lithosphere and major crustal structures exist or once existed.
Figure 4.7 Major Archean and Proterozoic provinces in Australia and the location of intrusion-hosted Ni-Cu sulfide ± PGE deposits, showing that the deposits are located near to Precambrian province boundaries. Province geometries are from Geoscience Australia’s Provinces GIS dataset (Stewart et al., 2013).
Imaging of lithospheric architecture has improved steadily in Australia through acquisition of new seismic tomographic data, extensive deep reflection seismic data, high-resolution potential-field data, and recent continental-scale isotope data (e.g. Kennett et al., 2013b; Champion, 2013). Here we use one dataset to identify regions of thinner lithosphere and two datasets to identify major crustal boundaries and crustal scale faults, which may have acted as major melt pathways. The latter two datasets also act as potential proxies for regions of previously thinner lithosphere, given that changes in lithosphere thickness may occur across major crustal boundaries.

### 4.2.2.1 Mappable criterion and datasets: boundaries of lithospheric blocks

Analysis of seismological data reveals that most of the Australian continent is underlain by lithosphere greater than 150 km thick (Figure 4.8; McKenzie and Priestley, 2008; Kennett et al., 2013a; Czarnota et al., 2014; Yoshizawa, 2014). Many LIPs and high-Mg basalts discussed in this report overlie this region of thick lithosphere, indicating that some time in the past the lithosphere was much thinner. It is also well established that the Australian continent is an amalgamation of different lithospheric blocks with discrete geological histories, geothermal gradients and mantle compositions (e.g., Myers et al., 1996; Cawood and Korsch, 2008). The boundaries of these blocks may mark the interfaces between lithospheric domains of differing thickness and composition before they were amalgamated. Such
boundaries potentially guided the ascent of mantle-derived melts, whether fossilised within what is now thick continental lithosphere or at the margins of the currently thick lithospheric root of the continent. Seismic tomography is one method of mapping the distribution of these lithospheric blocks where they are characterised by different seismic velocities.

![Seismic tomography images](image)

Figure 4.9 Vertical component of shear-wave velocity (Vsv) shown at four depth slices from the Australian Seismological Reference Model, mantle component, with a horizontal spatial resolution of 0.5° x 0.5° (Kennett et al., 2013a). (A) 100 km, (B) 150 km, (C) 200 km, and (D) 250 km.

Here we exploit the vertical component of the shear wave velocity (Vsv) as it is the best constrained aspect of the mantle component of the Australian Seismological Reference Earth Model (AuSREM; Figure 4.9; Kennett et al., 2013a). In order to map the locations of present and past boundaries of lithospheric blocks we have calculated horizontal gradients in Vsv in the mantle above the lithosphere-asthenosphere boundary for a series of depth slices with 50 km vertical spacing (Figure 4.10). The depth slices of the horizontal gradient of Vsv (Figure 4.10) were then combined into a single map, so
as to minimise the uncertainties in the dataset used in the mineral potential modelling. Figure 4.11 shows the values of horizontal gradients in the shear-wave velocity (ΔVsv) above the lithosphere-asthenosphere boundary after summing the values for all of the depth slices and then dividing this total value by the number of depth slices occurring above the lithosphere-asthenosphere boundary at each location. This is referred to as the normalised average ΔVsv within the lithosphere. The resultant map purposefully emphasises the stronger horizontal gradients in Vsv, more likely to represent steeper and more vertically-extensive boundaries between lithospheric blocks. The most prominent features in Figure 4.11 are the strong gradients in the present-day lithosphere-asthenosphere boundary (cf. Figure 4.8). However, second-order features such as the north-south trending high to the north of the Great Australian Bight may represent an old lithospheric block boundary. It is only those gradients which persist across multiple depth slices at roughly the same latitude and longitude that appear as high values in Figure 4.11.

Figure 4.10 Horizontal gradient of the shear-wave velocity (ΔVsv) shown at four depth slices from the Australian Seismological Reference Model, mantle component. (A) 100 km (B) 150 km (C) 200 km and (D) 250 km.

Figure 4.10 Horizontal gradient of the shear-wave velocity (ΔVsv) shown at four depth slices from the Australian Seismological Reference Model, mantle component. (A) 100 km (B) 150 km (C) 200 km and (D) 250 km.
4.2.2.2 Mappable criteria and datasets: major crustal domain boundaries using Major Crustal Boundaries and neodymium isotope-based boundaries

Two datasets were utilised to map major crustal domain boundaries: one based on seismic reflection data and another based on neodymium (Nd) isotope mapping. Each is described below.

Major boundaries between crustal blocks are a mappable criterion representing lithospheric architectural elements favourable for transfer of mantle-derived melts into and through the crust. Major crustal boundaries have been imaged in many deep crustal seismic reflection profiles and in some cases may mark ancient plate boundaries. However, it should be noted that such boundaries do not necessarily relate directly to boundaries in the mantle lithosphere. The Major Crustal Boundaries of Australia Dataset (Korsch and Doublier, 2014) synthesises more than 30 years of deep seismic reflection data across Australia, and maps major crustal-scale breaks that have been interpreted in the seismic reflection profiles. Geological data (e.g., outcrop mapping, drill hole logs, and geochronology) and geophysical data (e.g., aeromagnetics, gravity) have been used to extrapolate and interpolate the crustal boundaries in areas distant from the seismic profiles.
Figure 4.12 Major crustal-scale boundaries displayed by confidence level. The boundaries are interpreted from seismic reflection profiles, which are also shown, as well as other geological and geophysical data.

Each boundary is given a confidence level (high to none), which reflects the proximity to the locations with highest certainty (i.e., the seismic lines) used to define the boundary (Figure 4.12). Presently, the dataset does not differentiate trans-crustal (i.e. mantle-tapping) structures from major intra-crustal structures. One data layer has been created using the boundaries identified by this dataset (with a 50 km buffer).

The second dataset utilised in this mineral potential study that maps crustal domain boundaries is based on Nd isotope mapping of model ages. For Ni-Cu-PGE ore-forming systems a number of important features are identifiable, either directly or indirectly, in regional Nd isotopic maps of two-stage depleted mantle model ages, which are based on whole-rock analyses of felsic igneous rocks (Champion, 2013; Champion and Huston, 2015). Variations in Nd isotopic compositions in part reflect
differences in the ages of the crustal material from which the felsic igneous rocks were sourced. In some circumstances this allows identification of the spatial extents of ancient cratonic blocks, even where they may have amalgamated during later tectonic processes. In this way, the extents of crustal blocks favourably endowed with mineral resources may be mapped, and their boundaries identified. Mapping variations in Nd and other radiogenic isotope compositions in rocks and minerals also can identify terranes of more juvenile (mantle-influenced) character, which may indicate regions of possible rifting and associated mineralisation (e.g., Huston et al., 2014).

The direct use of the Nd isotope model age data was considered for the present study, and in particular the horizontal gradients in the contoured map data (Figure 4.13). Zones with strong lateral gradients are assumed to represent significant changes in crustal composition and hence may mark boundaries between crustal blocks. However, the uneven distribution of source data means that calculated horizontal gradients will have large uncertainties in many areas. An alternative approach was therefore developed using a dataset of boundaries inferred from the contoured Nd isotope data. The Isotopic Domain Boundaries of Australia dataset (Champion, 2015) shows the locations of inferred boundaries of Nd isotopic domains (Figure 4.13). Due to the variable and commonly low density of isotopic data points, the dataset provides only broad spatial constraints on the crustal architecture of Australia. The boundaries are most robust in areas of higher data density.

Despite this limitation the Nd isotope-based boundaries provide crucial time-based information on the internal crustal architecture within those provinces for which abundant data are available. The best documented example pertinent to the current study is the Yilgarn Craton, where the great majority of komatiite-hosted nickel sulfide deposits occur along the strong gradient in Nd isotope model age between the Eastern Goldfields Superterrane in the east and the Youanmi Terrane to the west (Cassidy and Champion, 2004; Cassidy et al., 2005; Huston, et al. 2005). This fossil boundary remains evident as a strong east-west gradient in the Nd isotope model age data even though this zone is interior to the present-day margin of the Yilgarn Craton.

Two main procedures were adopted to create the Isotopic Domain Boundaries of Australia dataset. In areas of high data density (and high confidence), such as the Yilgarn Craton in Western Australia, isotopic data alone were used to delineate crustal domains. In areas of moderate data density (and correspondingly moderate confidence) (smoothed) boundaries of known geological provinces (e.g., from Shaw et al., 1996 and Geoscience Australia’s Provinces database) were used as a proxy for the isotopic boundaries. For both high and moderate data densities identified crustal boundaries were extrapolated (with correspondingly less confidence) into regions of lower data density. Only isotopic boundaries with high or moderate confidence have been used in this prospectivity analysis. A data layer has been created using the boundaries identified by this dataset (with an arbitrary 50 km buffer), with high-confidence boundaries given a higher weighting than medium-confidence boundaries.
Figure 4.13 Interpreted crustal domain boundaries, based on Sm-Nd isotope data, superimposed on colour-contoured two-stage depleted mantle Nd isotope model ages ($T_{2DM}$) map of Australia. The locations of isotope samples used to create the grid are shown as points, colour coded by magmatic age. Nd basement domain boundaries were inferred based on the Nd model age gradients in areas of available data and on geological province boundaries in areas of lower data density. Each boundary has been given a confidence level based on data density, which were used to create an input layer for the mineral potential study.

4.2.3 Results for mineral system component: lithospheric architecture

The three datasets described above were weighted with the values from Table 3.2 and then summed by overlaying the rasters to yield a map of fuzzy membership values of the lithospheric architecture component of the mineral system, shown in Figure 4.14. The areas of highest values, representing most favourable lithospheric architecture, occur where stronger horizontal gradients in shear-wave velocity in the mantle (represented by normalised average $\Delta V_{sv}$) spatially coincide with crustal domain boundaries as mapped using controls from seismic reflection and Nd isotope variations. The area of high values in a north-south zone near the west coast of southern Western Australia corresponds to the present-day margin between the Yilgarn Craton and the Perth Basin and underlying Pinjarra Orogen and coincides with the Darling Fault. The main normal movement on the Darling Fault was between the Early Triassic and the Middle Jurassic but there is evidence to suggest that the fault follows a line of crustal weakness initiated in the Archean (Lasky, 1993), and is also marked partially by the ~1210 Ma Marnda Moorn LIP (Pirajno and Hoatson, 2012). The southeast margin of the Yilgarn
Craton, east-southeast margin of the Pilbara Craton, and substantial areas of the Lachlan Orogen also appear favourable in terms of lithospheric architecture component of Ni-Cu-PGE sulfide mineral systems. The area of high values in the Cape York region of northern Queensland includes the Palmerville Fault, which marks the western margin of the Mossman Orogen. This fault, which has experience a long history of movement (de Keyser, 1963), represents a crustal domain boundary between the Paleozoic Tasmanides and generally Precambrian cratonic crust to the west (Hill, 1951; Direen and Crawford, 2003).

Figure 4.14 Variation in values of the ‘lithospheric architecture’ component in the mineral potential modelling. High values are most favourable. This input raster contributes 25% of the final mineral potential output.
4.3 Mineral system component: sources of ore metals – Ni, Cu, PGE

4.3.1 Introduction

Three theoretical criteria for the sources of ore constituents component of the mineral system are considered essential in the formation of major tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits. These have been mapped according to seven mappable criteria and using five datasets (Table 4.4).

Table 4.4 Theoretical criteria, mappable criteria and datasets for the sources of ore metals component of tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineral systems. Extract from Table 3.2.

<table>
<thead>
<tr>
<th>Mineral system component</th>
<th>Theoretical criteria</th>
<th>Mappable criteria</th>
<th>Dataset(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources of ore metals: Ni, Cu, PGE</td>
<td>Moderate to high degrees of partial melting to release nickel from olivine (and PGEs from sulfides and PGMs)</td>
<td>Geological unit polygons, points and lines with “ultramafic” or “ultramafic-mafic” in the bulkComposition field</td>
<td>The Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tholeiitic composition of magmas</td>
<td>Geological unit polygons, points and lines with “ultramafic-mafic” in the bulkComposition field</td>
<td>The Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
</tr>
<tr>
<td></td>
<td>High chalcophile-element abundances (Ni, PGE, Cu)</td>
<td>Geological units and events with ≥12% MgO</td>
<td>OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mafic rocks classified as tholeiitic</td>
<td>OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Ni (95th percentile)</td>
<td>OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014); Ni+Cu+PGE combined into single dataset</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Cu ≥ 180 ppm (90th percentile)</td>
<td>OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014); Ni+Cu+PGE combined into single dataset</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High PGE Pt ≥ 10 ppb or Pd ≥ 10 ppb</td>
<td>OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014); Ni+Cu+PGE combined into single dataset</td>
</tr>
</tbody>
</table>

4.3.2 Theoretical criterion: moderate to high degrees of partial melting

To form an economic Ni-Cu-PGE deposit the primary mantle-derived magma must contain sufficient concentrations of ore metals (Arndt et al, 2005). Figure 4.15 shows that komatiites, picritic and tholeiitic ocean island basalts, and continental flood basalts contain high Ni, Cu and PGE concentrations relative to average continental crust and mid-ocean ridge and some alkali basalts.
Figure 4.15 Total concentrations of Cu (ppm), Ni (ppm), Pt (ppb), Pd (ppb), and Au (ppb) in selected rock types illustrating that komatiites, continental flood basalts, and tholeiitic and picritic ocean island basalts have higher Ni, Cu, Pt and Pd contents than the other basalts and more silica-rich rocks. OIB = ocean island basalt, MORB = mid-ocean ridge basalt. Sources of data: Hoatson and Lewis (2014) with original data from Wedepohl (1995), McDonough and Sun (1995), Crocket (2002), Bennett (2003), Peck and Keays (1990).

The abundances of Ni, PGEs and Cu in magmas are controlled by the nature and abundances of silicate, sulfide, oxide and alloy minerals in the source mantle, which host these elements (Arndt et al., 2005). For example, nickel in the mantle is predominantly hosted by olivine and therefore the Ni content of magmas increased proportionally with the olivine content of the melted mantle (Maier and Groves, 2011). Similarly, the PGEs are mainly hosted in Cu-rich sulfide and platinum-group minerals.

Magnesium-rich basaltic, picritic and komatiitic melts have relatively high Ni, Cu and PGE contents because they are the products of medium to high degrees of partial melting (~20-50%) of the mantle, sufficient to melt or partially melt the host minerals of these metals (Figure 4.16). Notably, these rocks (or their plutonic equivalents) host most of the world's large nickel sulfide deposits (e.g., Naldrett, 2004).

Magnesium-rich magmas, such as komatiitic and picritic magmas, are also important in the formation of nickel sulfide ores because they are among the few mafic and ultramafic magma types that are sulfur-undersaturated at the time of magma formation (Keays, 1995).
Variations in the nature of the partial melt are caused by successive melting of the major silicate minerals.

Source: modified from Arndt et al. (2005).

4.3.2.1 Mappable criteria and datasets: moderate to high degrees of partial melting

Three mappable proxies for moderate to high degrees of partial melting have been utilised in this study (Table 4.4), all based on the premise that the presence of high-Mg rocks indicates generation of parent magmas via moderate to high degrees of partial melting. Two of the mappable criteria are based on the mapped presence of ultramafic rocks in Australia, with the corresponding datasets derived from the Australian Mafic-Ultramafic Magmatic Events dataset. Details of the method are presented in Appendix B. In summary, within this dataset the bulk composition of each unit was recorded in the bulkComposition field of the Geological Unit table as:

- Mafic
- Ultramafic
- Ultramafic-mafic
- Mafic-ultramafic

This bulkComposition field was used to create two layers that map the occurrences of ultramafic-bearing magmatic units and events. The first layer contains all polygons, points and lines attributed with “ultramafic” or “ultramafic-mafic” in the bulkComposition field. The second layer was created by extracting those polygons, points and lines attributed with “mafic-ultramafic” in the bulkComposition field. The latter layer was given a lower weighting in the GIS modelling as it is assumed that the ultramafic component of the unit is of a lower proportion within that unit or event. Rocks labelled as only having a “mafic” component in the bulkComposition field were not used as not all mafic rocks are prospective for nickel sulfide deposits.

The third mappable criterion representing moderate to high degrees of partial melting utilises geochemical data to map rocks with ≥ 12 weight percent MgO. As described in Appendix B, this dataset is derived from three sources: the Australian Mafic-Ultramafic Magmatic Events dataset...
(Thorne et al., 2014), Geoscience Australia’s OZCHEM database of whole-rock geochemical data, and a new dataset that links these two via a new classification of mafic and ultramafic compositions (Champion and Dulfer, 2015). High-Mg rocks including picrites and komatiites were selected using the criterion: MgO ≥ 12 weight percent (after Le Bas, 2000).

Note that included in all three datasets representing the mappable criteria, some of the ultramafic and high-Mg rocks will be cumulates (e.g. some dunites) and hence will not be representative of melt compositions. Nevertheless, the mineral potential analysis has included these mappable criteria in order to capture all known occurrences of ultramafic and high-Mg rocks (some of which will represent melt compositions) using the available datasets. Ideally, future prospectivity studies could be refined by excluding rock units and analyses of cumulates.

4.3.3 Theoretical criterion: tholeiitic magma compositions

Empirical evidence indicates that all major magmatic Ni-Cu-PGE sulfide ore deposits are hosted by, or affiliated with, tholeiitic magmas (Table 2.1, Table 2.2; see also Naldrett, 2004; Arndt et al., 2005; Hoatson et al., 2006; Begg et al., 2010). Although some alkalic mantle-derived magmas may contain elevated PGEs on account of their relatively oxidised nature (facilitating sulfide breakdown even during low-degree partial melting), few significant Ni-Cu-PGE are associated with such magmas. Arndt et al. (2005) argued that, for the Noril’sk system, the volatile-rich lower density alkalic magmas failed to interact efficiently with crustal rocks during their ascent, whereas the denser tholeiitic components passed through a series of crustal magma chambers where they assimilated crustal wall rocks, leading to sulfur saturation.

4.3.3.1 Mappable criterion and datasets: mafic rocks classified as tholeiitic

Mappable proxies for tholeiitic magma compositions are mafic volcanic and intrusive rock samples and geological units of tholeiitic chemical composition. Champion and Dulfer (2015) classified the mafic analyses (<12 weight percent MgO, i.e., after removal of picritic and ultramafic rocks) within the OZCHEM Whole-rock Geochemistry Dataset (Champion et al., 2007) as alkaline, tholeiitic, or undifferentiated, based on major and trace element compositions and by using various discrimination diagrams (see Champion and Dulfer, 2015 for details). The chemical analyses classified as tholeiitic in this dataset were used to create the input layer following the workflow described in Appendix B. The resulting raster dataset is illustrated in Figure 4.17.
Figure 4.17 Input raster for the ‘mafic rocks classified as tholeiitic’ mappable criteria. Geochemical point data with tholeiitic compositions (based on OZCHEM data) have been extrapolated to geological units and events using the Australian Mafic-Ultramafic Magmatic Events dataset (described in Appendix B). Areas coloured blue were weighted ‘low’ because tholeiitic units are subordinate to other rock types in these magmatic units and events. Areas coloured orange represent magmatic units and events contained tholeiitic extrusive rocks as the dominant rock types. The units and events with highest weighting, coloured red, are where the dominant rock types are tholeiitic mafic intrusive rocks. Intrusive rocks are the target hosts for the Ni-Cu-PGE sulfide deposits modelled, and hence are weighted more highly than extrusive rocks and events.

4.3.4 Theoretical criterion: high chalcophile-element abundances (Ni, Cu, PGE)

Some of the most significant controls on the potential of magmas for Ni-Cu-PGE mineralisation (‘fertility’) are the timing of sulfur saturation and the volumes of immiscible sulfide liquid (e.g., Naldrett, 2004). Early sulfur saturation, either during partial melting of the mantle or during ascent into the crust, may result in sequestering of much of the chalcophile element budget into sulfide melt, resulting in magmas depleted in these elements and rendering such systems non-fertile for development of major Ni-Cu-PGE deposits. As outlined in numerous studies (e.g., Naldrett, 2004; Arndt et al., 2005) sulfur saturation just prior to or during final emplacement of the intrusion in the crust, but before significant olivine crystallisation, is a common feature in many of the world’s largest Ni deposits (Naldrett, 2004; Arndt et al., 2005). It is also a requirement, however, that the immiscible sulfide liquid is able to interact with sufficient volumes of Ni-Cu-PGE-bearing silicate melt to form deposits of economic grade and tonnage.
4.3.4.1 Mappable criteria and datasets: high chalcophile-element abundances (Ni, Cu and PGE)

The most obvious indicators of fertile magmas are the relative abundances of the ore elements (Ni, Cu, and PGE), i.e., magmas with elevated levels of these elements are most favourable, all other variables being equal (Figure 4.18). Such elevated levels of these elements are assumed to be indicative of magmas where early sulfur saturation (i.e., in the mantle source) did not occur. However, it is recognised that elevated Ni, Cu and PGE values in some cases may not represent the abundances in the parent magmas but may relate to other processes such as (i) formation of Ni-bearing olivine in cumulates; (ii) presence of mineralisation, (iii) post-magmatic mobilisation of Ni, Cu and/or PGEs during metamorphism, hydrothermal activity, or weathering.

We have chosen to use Ni, Cu, and the PGEs Pt and Pd abundances as mappable proxies of magma fertility. Each exhibits chalcophile behaviour in the presence of sulfide melt, with the PGEs more sensitive and reliable than Ni or Cu in recording the evolution of sulfur in the magmas. However, the use of the PGEs suffers from the fact that only a small percentage of OZCHEM samples have been analysed for PGEs. In contrast nearly all OZCHEM samples have been analysed for Ni and Cu, although both elements suffer from additional complexities, such as the high mobility of copper in hydrothermal fluids and groundwater, and the strong partitioning of Ni into olivine coupled with the important role of olivine in the generation and evolution of ultramafic and mafic melts.

In order to map chalcophile-element enrichments, a new dataset was created that links OZCHEM geochemical analyses of mafic-ultramafic rocks with the Australian Mafic-Ultramafic Magmatic Events dataset (Champion and Dulfer, 2015). This powerful tool allows extrapolation of the geochemical point data to identify other potentially related igneous rocks within the same magmatic event. Datasets were developed first for Ni, Cu and PGE enrichments and then combined into a single input raster for the GIS modelling. The methodology is described in Appendices B and C.

High nickel abundances. The methodology for calculating enrichments in Ni is based on a statistical treatment of all available data in the OZCHEM database (~8500 samples). In summary, for each particular value of MgO (a measure of the extent of magmatic fractionation), samples with Ni abundance above the 95th percentile were selected. The units and events in the dataset of Thorne et al. (2014) within which these samples occur were then attributed accordingly as being enriched in Ni.

High copper abundances. Elevated Cu values were calculated statistically for the entire geochemical dataset with the threshold value set at the 90th percentile, i.e., Cu > 180 ppm. Using this criterion 704 samples were selected (out of a possible ~8500).

High PGE abundances. Elevated PGEs levels were calculated using Pt and Pd only—the only members of the PGE group for which significant data were available (515 out of the ~8500 sample dataset with Pt and/or Pd data). Thresholds were set at 10 ppb for both elements, corresponding to the 75th percentile for Pd and the 90th percentile for Pt. Samples were chosen with either Pt or Pd greater than 10 ppb (189 samples selected). This included both samples with Pd > 10 ppb and Pt < 10 ppb, and vice versa.
Figure 4.18 Input raster of high chalcophile-element abundances. The areas with the highest values are intrusions with elevated Ni and/or Cu and/or PGEs.

4.3.5 Results for mineral system component: sources of ore metals – Ni, Cu, PGE

The three datasets described above were weighted with the values from Table 3.2 and then summed by overlaying the rasters to yield a map of fuzzy membership values of the sources of ore metals component of the mineral system, shown in Figure 4.19. The areas of higher value are intrusive rocks with favourable geochemistry (e.g. Mg-rich tholeiitic units and events and with elevated Ni and/or Cu and/or PGEs). Figure 4.20 examines areas of Australia in greater detail. Figure 4.20A shows the Musgrave Province in central Australia where intrusions of the Giles Complex, a part of the Warakurna LIP, are highlighted as very favourable in terms of ore metal fertility. Also highlighted in Figure 4.20A are the Alcurra Dolerite Dyke Swarm, a part of the Gairdner LIP, and intrusions in the southern Arunta Province. In the Yilgarn Craton (Figure 4.20B) there are a large number of areas of Archean mafic and ultramafic rocks with moderate to high favourability (orange) for the ore metals component of the mineral system. However, due to the fact that almost of these polygons have not been subdivided in terms of magmatic events or intrusive versus extrusive in the dataset of Thorne et al. (2014), they appear with high values in Figure 4.19 and Figure 4.20B. Although most are komatiitic lavas, some komatiitic intrusions may be present (such as at the Mt Keith deposit) and hence these ‘undefined’ units have been retained in the modelling.
In the Pilbara Craton in Western Australia (Figure 4.20C) there are extensive komatiitic flows within sedimentary sequences, such as the Kylena Formation, Maddina Formation and June Hill Volcanics, which have low values of favourability for the sources of ore metals component. However, there are also a number of intrusive mafic to ultramafic rocks in the northern Pilbara Craton that are highlighted with high values. These include the Millindinna Intrusion, Regal Formation and the Andover Intrusion – units that correlate well with known PGE and Ni-Cu sulfide mineralisation within the Munni Munni and Radio Hill Intrusions (e.g., Munni Munni: 20-30 Mt @ 2.9 ppm Pt+Pd+Au, 0.3% Cu, 0.2% Ni; Hoatson et al., 1992). In the Phanerozoic of eastern Australia the Micalong Swamp Basic Igneous Complex is modelled with moderate to high favourability for the ore metals, due to the presence of tholeiites with both high MgO and elevated chalcophile-element contents (Figure 4.20D). Interestingly, there are a number of known PGE-enriched magmatic units in the Lachlan Orogen that exhibit low favourability as sources of ore metals in the modelling. Examples include the Alaskan-type complexes of the Fifield region (Barron et al., 2004). The low model values for this mineral system component may be due to the non-tholeiitic compositions of most of the mafic and ultramafic intrusions in this region.
4.4 Mineral system component: Ore depositional gradients

4.4.1 Introduction

Five theoretical criteria for the ore depositional gradients component of the mineral system have been identified as key processes or features in the formation of major tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits. These are represented by seven mappable criteria although three of these are combined into one dataset, so that five datasets are used as inputs in the GIS modelling (Table 4.5).
Table 4.5 Theoretical criteria, mappable criteria and datasets for the ore depositional gradients component of tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineral systems. Extract from Table 3.2.

<table>
<thead>
<tr>
<th>Mineral system component</th>
<th>Theoretical criteria</th>
<th>Mappable criteria</th>
<th>Dataset(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ore depositional gradients</strong></td>
<td>Chalcophile element depletions in magmatic systems at crustal levels</td>
<td>Ni depletion (50th percentile)</td>
<td>OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Depleted Cu Cu ≤ 10 ppm (10th percentile)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ni+Cu+PGE combined into single dataset</td>
</tr>
<tr>
<td></td>
<td>Sulfur-saturation and segregation of immiscible Ni-Cu-PGE rich sulfide melt at crustal levels</td>
<td>Sulfur-saturated igneous rocks. High sulfur S ≥ 1540 ppm (90th percentile)</td>
<td>OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al. 2014)</td>
</tr>
<tr>
<td></td>
<td>Evidence of near-surface mafic-ultramafic hosts to mineralisation</td>
<td>Surface geochemical expressions of mafic-ultramafic rocks and/or magmatic mineralisation</td>
<td>National Geochemical Survey of Australia (de Caritat and Cooper, 2011); river catchment polygons (McPherson et al., 2011); NGSA principle component PC3 (de Caritat and Grunsky, 2013)</td>
</tr>
<tr>
<td></td>
<td>Formation of Ni and PGE mineralisation</td>
<td>Mineral occurrences with Ni and/or PGEs as the primary commodities</td>
<td>Australian Atlas of Mineral Resources; OZMIN Mineral Deposits Database (Ewers et al. 2002)</td>
</tr>
<tr>
<td></td>
<td>Mafic and ultramafic host rocks at shallow-crustal (explorable) depths</td>
<td>Regional gravity and magnetic anomalies</td>
<td>Bouguer Anomaly Gravity Grid (Bacchin, 2009)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Magnetic Intensity (TMI) (Nakamura and Milligan, 2015)</td>
</tr>
</tbody>
</table>

4.4.2 Theoretical criterion: Chalcophile-element depletions in magmatic systems at crustal levels

Nickel, Cu and the PGE behave as chalcophile elements in the presence of sulfide liquids and will be strongly partitioned from silicate melt into sulfide liquid that has separated via immiscibility. In magma systems where Ni-Cu-PGE-rich immiscible sulfide liquid is removed from its parent silicate melt (e.g., by gravity settling), or in systems where the silicate melt has interacted with pre-existing sulfide liquids, (e.g., in conduits during emplacement), then the residual silicate melt will be depleted in the chalcophile elements relative to its initial composition. Therefore, it is expected that the crystallised products of such magma systems, whether intrusive or volcanic, will exhibit evidence of both Ni-Cu-PGE enrichment (i.e., mineralisation) and depletion in different parts of the igneous complex. Enrichments and depletions represent changes in composition through time and/or spatially within the magmatic system, hence the use of the term ‘ore depositional gradients’ for this component of the mineral systems.

Recognition of mafic or ultramafic rocks with depleted chalcophile element contents is thus considered a positive indicator of Ni-Cu-PGE sequestration in another part in the magmatic system. The most favourable scenario for mineral exploration is where sulfur saturation and Ni-Cu-PGE concentration occurs not in the mantle or deep crust but in mid- to upper-crustal magma chambers that are subsequently exhumed to near-surface, explorable, depths. The GIS modelling in this study aims to identify mafic-ultramafic magmatic systems characterised by both enrichments and depletions in chalcophile elements. Depletions may occur either within intrusive complexes and/or within ‘outflow’
parts of magmatic systems, as represented, for example, by volcanic rocks. Clearly, such volcanic rocks are not themselves prospective but indicate that Ni-Cu-PGE sulfide concentrations may exist elsewhere in the intrusive-extrusive system. One example is the Paleoproterozoic Eastern Creek Volcanics in the Mt Isa region of northwest Queensland in which low chalcophile-element contents in the Cromwell Metabasalt Member have been interpreted as due to sequestration by sulfide liquids elsewhere in the magmatic system (Gregory et al., 2008). The challenge in this case is to locate the co-magmatic intrusions that may host Ni-Cu-PGE mineralisation.

4.4.2.1 Mappable criteria: Depleted chalcophile-element abundances (Ni, Cu and PGE)

This study utilises Ni, Cu, Pt and Pd as mappable indicators of depletion. Each exhibits chalcophile behaviour in the presence of sulfide liquid, with the PGEs more sensitive and reliable than Ni or Cu in recording the evolution of sulfur in the magmas. However, the use of the PGEs suffers from the fact that only a small percentage of OZCHEM samples have been analysed for PGEs. In contrast nearly all OZCHEM samples have been analysed for Ni and Cu, although both elements suffer from additional complexities, such as the high mobility of copper in hydrothermal fluids and groundwater, and the strong partitioning of Ni into olivine coupled with the important role of olivine in the generation and evolution of ultramafic and mafic melts.

In order to map chalcophile-element depletions, the same general methodology was used as in mapping chalcophile element enrichments (see above, and Appendices B and C). This involved linking OZCHEM geochemical analyses of mafic-ultramafic rocks with the Australian Mafic-Ultramafic Magmatic Events dataset (Champion and Dulfer, 2015), which allows identification of other potentially related igneous rocks within the same magmatic event. Datasets were developed first for Ni, Cu and PGE depletions and then combined into a single input raster for the GIS modelling.

Depletions in Ni. The methodology for calculating depletions in Ni is based on a statistical treatment of all available data in the OZCHEM database (~8500 samples). In summary, for each particular value of MgO (a measure of the extent of magmatic fractionation), samples with Ni abundance below the 5th percentile were selected. The units and events in the dataset of Thorne et al. (2014) within which these samples occur were then attributed accordingly as depleted in Ni.

Depletions in Cu. Depleted Cu values were calculated statistically for the whole geochemical data set with the threshold value set at the 10th percentile, i.e., Cu ≤ 10 ppm. Using this criteria 796 samples were selected (out of a possible 8500).

Depletions in PGEs. Depleted PGE levels were calculated using Pt and Pd only—the only members of the PGE group for which significant data were available (596 out of the ~8500 sample data set with Pt and/or Pd data). Thresholds were set at 1 ppb for either element (at the detection limit for most analyses for both Pd and Pt). Samples were chosen with either Pt or Pd less than 1 ppb (252 samples selected). This included both samples with Pd > 1 ppb (238 samples) and Pt ≤ 1 ppb, and vice versa (241 samples). In actuality, this produced a dataset where Pt and Pd were both ≤ 2 ppb.

Figure 4.21 shows the depleted Ni, Cu and PGE data combined into one layer.
4.4.3 Theoretical criterion: sulfur saturation and segregation of immiscible Ni-Cu-PGE-rich sulfide melt at crustal levels

Most mafic and ultramafic magmas with sulfur contents typical of their mantle sources will attain sulfur saturation only very late in their crystallisation evolution. This is particularly so if emplaced at mid- to shallow-crustal levels where the parent magmas will be moderately to strongly under-saturated with respect to sulfide (Mavrogenes and O’Neill, 1999). This common scenario is not favourable for Ni-Cu-PGE sulfide ore formation because (a) the volume fraction of immiscible sulfide liquid is small, and (b) most of the Ni will have already been partitioned into olivine (and other minerals), although most of the Cu and PGE may be retained in the late-stage silicate melts. Extraordinarily efficient sequestering of Ni, Cu and PGE and concentration of sulfide melt would be required to form ore deposits of significant size in such ‘normal’ magmatic systems, though it is a viable process for ultramafic magmas, as shown by komatiite-associated nickel mineralisation.

Also unfavourable, at least on theoretical grounds, are scenarios in which sulfur saturation occurs in the mantle or lower crust, leaving the residual magmas depleted in chalcophile elements when they are emplaced at higher levels in the lithosphere. While this may not rule out the formation of Ni sulfide mineralisation, if only small volume fractions of sulfide melt segregate in the mantle or lower crust, it
may result in PGE depletion due to the higher sulfide-silicate melt partition coefficients and lower abundances of the PGE compared with Cu or Ni. The Nain Plutonic Complex, hosting the Voisey’s Bay deposit, is an example where early, mantle-level, sulfur saturation (Scoates and Mitchell, 2000) evidently did not limit the capacity of the system to develop a major Ni sulfide deposit but may have constrained the PGE content in the deposit.

Ideally for the formation of large intrusion-hosted Ni-Cu-PGE sulfide deposits are scenarios in which sulfur saturation occurs relatively early in the crystallisation evolution, before significant volume fractions of Ni-bearing olivine have crystallised. Sulfur saturation at this stage is generally considered to require either addition of sulfur to the melt and/or other changes to the melt composition that may induce sulfur saturation such as increased silica content (e.g., see discussion in Naldrett, 2004). Assimilation of sulfur-bearing and/or siliceous crustal wall rocks, and magma mixing, are widely agreed as likely processes causing sulfur saturation in magmatic systems hosting major Ni-Cu-PGE sulfide deposits. These represent ‘ore depositional gradients’ in composition through time and/or spatially in the magmatic system. Crustal contamination may be recognised in shifts in isotopic composition (e.g., S, Nd, Sr) and in whole-rock geochemical composition, but insufficient data are presently available at the national scale to utilise such tracers in the present study. We have, therefore, used the more widely available sulfur contents of mafic and ultramafic rocks, from whole rock geochemical analyses, as a proxy for evidence of early sulfur saturation, selecting only the highest values so as to eliminate samples representing ‘normal’ (i.e. late-stage) sulfur saturation with sulfides disseminated throughout the magma. It is assumed that if mafic-ultramafic magmas contained very high concentrations of sulfur then they would have attained sulfur saturation relatively early in their crystallisation history. Nevertheless, it should be noted that some of the high sulfur values also may be the product of processes unrelated to Ni-Cu-PGE sulfide formation, such as hydrothermal or metamorphic processes superimposed on the magmatic systems.

**4.4.3.1 Mappable criterion and dataset: sulfur-saturated igneous rocks**

Enriched S values were calculated statistically for the entire available geochemical dataset with the threshold value set at the 75th percentile (S > 1540 ppm). Using this criterion 1042 samples were selected. The method is described in Appendix B, using the combination of the OZCHEM database and the Australian Mafic-Ultramafic Magmatic Events dataset (Thorne et al., 2014).
4.4.4 Theoretical criterion: evidence of near-surface mafic-ultramafic hosts to magmatic mineralisation

Geological terranes containing mafic and ultramafic rocks and related orthomagmatic mineralisation (e.g., Ni-Cu-PGE, V, Cr, Ti, Sc) are variably exposed at the surface in Australia, and are commonly concealed by weathered materials, transported unconsolidated sediments, and by sedimentary basins. Outcrop of mafic and ultramafic rocks and sulfidic mineralisation is commonly weathered, in some cases very intensely and deeply, due to the instability of the primary silicate and sulfide minerals in the weathering environment. The erosion products of mafic and ultramafic rocks and related mineralisation in Australia therefore are likely to contain clays and secondary oxide minerals, as well as in some cases relict resistate minerals such as spinel (e.g., chromite), magnetite, ilmenite, platinum-group minerals and native PGE metals (e.g., as alloys), and perhaps pyrite. Modern sediments derived from outcropping or subcropping mafic and ultramafic rocks and related magmatic mineralisation are expected to preserve geochemical signatures of the source rocks, albeit diluted by sediment from other sources within a river catchment. Such signatures may indicate the near-surface presence of mafic or ultramafic rocks and/or associated magmatic mineralisation.
4.4.4.1 Mappable criterion and dataset: surface geochemical expression of mafic-ultramafic rocks and/or magmatic mineralisation

The mappable criterion corresponding to the theoretical criterion is a surface geochemical expression of mafic-ultramafic rocks and/or magmatic mineralisation. In order to map this criterion, the National Geochemical Survey of Australia (NGSA) has been used as a primary source of data. This survey sampled unconsolidated sediments at depths of 0 cm to 10 cm and 60 cm to 80 cm at the outlets of 1186 modern river catchments across Australia (de Caritat and Cooper, 2011). Sediment samples with different grain size fractions were analysed at each site for up to 68 elements. Principal Component Analysis of the results has revealed that one of the principal components, PC3, has positive values dominated by the elevated abundances of the elements Cr, Sc, V, Ti, Co and Ni (Figure 4.23; de Caritat and Grunsky, 2013). Furthermore, the spatial distributions of catchments with higher positive values of PC3 correspond well with the spatial locations of geological terranes with outcropping mafic and ultramafic rocks (de Caritat and Cooper, 2011; de Caritat and Grunsky, 2013). This spatial association is consistent with the fact that Cr, Sc, Ti, Co and Ni are all elevated in mafic and ultramafic rocks in comparison with most felsic and sedimentary rocks. The PC3 signature also may be indicative of the presence of resistate minerals of magmatic origin that have survived the weathering and surficial transport processes. Further work is required to test this hypothesis, such as inclusion of PGE data in the principal component analysis, and mineralogical work on NGSA samples.

While it is possible that the PC3 data in general are identifying only areas of mafic-ultramafic rock outcrop and subcrop and not magmatic Ni-Cu-PGE mineralisation directly, the most positive values potentially are indicating the presence of Cr- and Ni-rich mineralisation. For this reason we argue that the PC3 dataset of the NGSA is useful in this mineral potential study as a proxy for the presence in the near-surface of mafic and/or ultramafic rocks and/or magmatic mineralisation.
4.4.5 Theoretical criterion: formation of Ni and PGE mineralisation

Although Ni may behave as a chalcophile element in the presence of sulfide liquid, it also shows lithophile characteristics during magmatic fractionation processes. Ultramafic rocks dominated by olivine may contain up to ~2000-3000 ppm Ni, due to this lithophile behaviour of Ni. Such Ni contents do not constitute ore grade; higher grades require Ni sequestering by sulfide melt, which has a higher partition coefficient than olivine. Ore grades (i.e., percent levels) of Ni are a positive indicator of a ‘working’ magmatic mineralising system, but the volumes of Ni mineralisation must be large for mineralisation to be economic. Mineral occurrences as recorded in Geoscience Australia’s MINLOC database represent concentrations of metals above those of common rocks such as Ni-bearing dunites, although they do not qualify as mineral deposits due to generally small tonnages and/or low grades. Mineral occurrences bridge the gap in the continuum of size between single-sample geochemical anomalies recorded in OZCHEM and mineral deposits as recorded in Geoscience Australia’s OZMIN database. Mineral occurrences data are therefore useful in the GIS modelling of...
‘ore depositional gradients’ in showing where mineral systems have operated effectively, at least to produce sub-economic occurrences. The mineral occurrence points were given an arbitrary buffer of 1.5 km. Conversely, we have deliberately omitted using mineral deposit data from OZMIN in the prospectivity analysis because they would bias the results toward areas of known economic mineralisation. Instead, the mineral deposit information is used to validate the predictions of the modelling. Although the target mineral deposit type, intrusion-hosted Ni-Cu-PGE sulfide mineralisation, are Cu-bearing deposits Cu occurrences have not been included in this theoretical criterion or in the corresponding mappable criterion because the majority of Cu occurrences in the MINLOC database are not of this mineral deposit type.

4.4.5.1 Mappable criterion and dataset: mineral occurrences with Ni and/or PGEs as the primary commodities

Geoscience Australia’s MINLOC database was queried for all mineral occurrences in Australia with the elements Ni and/or the PGEs (Pt, Pd, Os or Ir) listed at the primary commodities.

Figure 4.24 Locations of mineral occurrences (not mineral deposits) containing nickel or one or more of the platinum-group elements (Pt, Pd, Os or Ir) as the first element listed in Geoscience Australia’s MINLOC dataset. Each occurrence was buffered to 1.5 km in the GIS modelling of the ‘ore depositional gradients’ component of the mineral system. Background coloured image is Geoscience Australia’s 1:5 million scale Geology of Australia.
4.4.6 Theoretical criterion: mafic and ultramafic host rocks at shallow-crustal (explorable) depths

Most tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits form at mid- to shallow-crustal levels within sill-dyke complexes and pipe-like ‘chonolith’ intrusions. These mafic to ultramafic igneous host bodies commonly are more dense than the crustal country rocks they intrude, and in many cases contain primary igneous magnetite. Sulfide mineralisation locally may enhance both the magnetic susceptibility (if pyrrhotite is present) and density. The combination of these rock properties results in many mafic and ultramafic intrusions exhibiting joint gravity-magnetic anomalies, with shallower bodies generally having higher amplitude anomalies with steeper horizontal gradients than deeper bodies. There are of course many exceptions and variations to this scenario, including for example altered and de-magnetised mafic-ultramafic bodies; magnetically reverse-polarised bodies; highly magnetic and dense rocks that are not mafic or ultramafic intrusions such as magnetite-bearing banded iron formations (BIF) and some hydrothermal and high grade metamorphic rocks.

4.4.6.1 Mappable criteria and datasets: regional gravity and magnetic anomalies

Notwithstanding the caveats above, the characteristics that can be mapped to identify the presence of mafic and ultramafic host rocks at shallow-crustal depths are the gravity and magnetic responses of such bodies. These are particularly useful in regions where the mafic-ultramafic rocks are concealed by sediments, basins and/or regolith zones.

The datasets used are the regional Bouguer Gravity Anomaly Grid of Australia and Total Magnetic Intensity Map of Australia (Bacchin, 2009; Nakamura and Milligan, 2015), which together should help constrain the locations of major volumes of mafic-ultramafic rock existing at shallow levels beneath Earth’s surface. False-positives (e.g., BIF) will tend not to be enhanced in other datasets in the modelling, such as the units and events polygons in the Australian Mafic-Ultramafic Magmatic Events GIS Dataset of Thorne et al. (2014). Deep-crustal mafic and ultramafic bodies will also tend to contribute to the Bouguer gravity and magnetic signals with lower amplitudes than shallow-crustal sources although exceptions doubtless will be present in the results. The low weightings given to the regional gravity and aeromagnetic datasets reflect the uncertainties discussed above.
Figure 4.25 Bouguer gravity of Australia input raster, based on the Bouguer Gravity Anomaly Grid of Australia (Bacchin, 2009).
4.4.7 Results for mineral system component: ore depositional gradients

The five datasets described above were weighted with the values from Table 3.2 and then summed by overlaying the rasters to yield a map of fuzzy membership values of the ore depositional gradients component of the mineral system, shown in Figure 4.27. This mineral system component has the largest number of input datasets, and so the higher values of favourability are due to a wide variety of reasons. Some notable areas with highly favourable ore depositional characteristics include: (a) the Fraser Complex in the Albany-Fraser Province, which hosts the Nova deposit; (b) magmatic complexes in the McArthur Basin and Pine Creek Orogen, Northern Territory, including the Derim Derim Dolerite, Oenpelli Dolerite and Zamu Dolerite; (c) west Pilbara Craton intrusions; (d) Giles Complex in the Musgrave Province; (d) southern Arunta Province; (e) east Kimberley region; (f) Mt Isa Inlier; (g) Cape York region; (h) western Gawler Craton; and (i) dolerites in parts of Tasmania.
Figure 4.27 Variation in values of the 'ore depositional gradients' component in the mineral potential modelling. This input raster contributes 25% of the final mineral potential output.
5 Ni-Cu-PGE sulfide mineral potential of Australia: Results

5.1 Overview of results

Figure 5.1 and Figure 5.2 (enlarged) show the total mineral potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia, derived by summing the results of each of the four mineral system components, as described in Appendix A. Each of the four result layers have been given equal weighting in the integrated mineral potential result, in order to honour the principle that all four components of the mineral system must be present at a particular place and time in order to form a major ore deposit.

The validity of the modelling results can be partly assessed by comparing these predictions with the locations of known tholeiitic intrusion-hosted Ni-Cu-PGE deposits in Australia (Figure 5.1). Although few deposits of this type are currently known in Australia, the locations of the largest examples (Nebo-Babel; Nova; Sally Malay) are successfully predicted in the modelling, occurring within or near areas modelled as having high mineral potential. It is important to note that mineral deposits were not included as inputs in the prospectivity modelling, as this would have biased the results. The power of the knowledge-driven mineral systems approach employed in the present study is in enabling predictions of mineral potential in regions where there are no known mineral deposits of the type sought, that is, in greenfields regions. The approach also permits predictions in areas where prospective basement is concealed by cover, because many of the input datasets represent geological features beneath the cover. These datasets include: (a) seismic tomography-based data (thickness of mafic rock in the crust; horizontal gradients of surface-wave velocity in the lithosphere); (b) reflection seismic-based interpretations of major crustal domain boundaries; (c) gravity and magnetics datasets; (d) interpreted basement geology polygons in the MUMs dataset for the central and western parts of the continent; and (e) neodymium isotope-based interpreted boundaries between crustal blocks.

The use of input datasets with highly variable spatial density, such as those involving OZCHEM whole rock geochemical analyses, which have been used for a significant number of input datasets, potentially may introduce biases such that areas of higher data density (typically regions of outcrop) may yield higher prospectivity. These effects of local enhancement of prospectivity in areas of higher data density have been partly mitigated by linking the geochemical data to the MUMs dataset (Champion and Dulfer, 2015), so that entire geological units and events within MUMs are also attributed with the characteristics of the spatially restricted geochemical point data, albeit with lower weightings than the buffered points themselves. This has the effect of ‘smearing’ the positive (as well as negative) features in the geochemistry over much broader areas than the sample points themselves. It also permits extrapolation of the geochemical characteristics from sample sites, which are generally located within outcrop, into areas where the sampled geological unit is concealed by cover sediments and regolith.

Nevertheless, it is recognised that the higher modelled prospectivity of some areas is partly due to a greater spatial density of data, particularly geochemical data. The modelling is therefore not identifying all possible areas of high mineral potential, and in this sense represents the minimum areas of potential. Additional areas of elevated prospectivity are expected to emerge if and when new data become available that allow the spatial distribution and resolution of the datasets (e.g., geochemical samples) to be enhanced.
Figure 5.1 The final result of the mineral systems analysis showing the potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia. Known deposits of this type (labelled) are shown to validate the results of the modelling; they were not used in the modelling.

Some areas modelled as high potential arguably may be false-positives, due to spatial overlaps of mineral system components that may be temporally unrelated. An example is the western margin of the Yilgarn Craton where the architecture contribution is high, along a present-day margin of a lithospheric block where there are large horizontal gradients of seismic velocity in the mantle, coinciding spatially with a large contribution from the energy source / driver component. Arguably, the development of this margin, which occurred during the breakup of Gondwana and separation of India from Australia, is younger than, and unrelated to, the major mafic and/or ultramafic magmatism known along this margin (e.g., Marnda Moorn LIP). The geochemical characteristics of the Marnda Moorn LIP enhance the prospectivity of the margin. However, we caution against ruling out this area of modelled high mineral potential as a false-positive because it is conceivable that a weakness was present in the lithosphere long before the breakup of Gondwana, which may have in part controlled the location of a segment of the Marnda Moorn LIP along this margin. Improved understanding of the temporal and spatial evolution of Australia’s lithospheric architecture will be required to better interpret the significance of some of the areas of modelled high potential. In the meantime, we propose that the highlighted areas deserve detailed interrogation and follow-up studies to test the proposals in the present assessment.
A further limitation of the mineral potential modelling in this study is the lack of inclusion of sulfur-bearing wall rocks in the ore depositional gradients component of the mineral system. Mafic and ultramafic magmas are normally sulfur undersaturated as they reach mid to upper crustal levels due to the inverse relationship between sulfur solubility and pressure (e.g. Mavrogenes and O'Neill, 1999). Therefore, a process must occur during emplacement to drive sulfur saturation. Sulfur isotope data indicate that the formation of most tholeiitic intrusion-hosted nickel deposits require the addition of external sulfur (by assimilation of crustal rocks) to induce sulfur immiscibility. Crustal rocks potentially able to contribute sulfur include black shales, paragneiss, banded iron formation (BIF), felsic volcanic rocks, sulfidic cherts, and evaporates. Therefore, an important theoretical criterion for the ore depositional gradients component of the mineral system is the presence of sulfur-bearing rocks, particularly within sedimentary basins. However, appropriate datasets were not available at the national scale, and therefore this theoretical criterion (nor corresponding mappable criteria or datasets) was not included in the prospectivity analysis.

Notwithstanding these limitations and caveats, the mineral potential modelling has successfully identified all of the magmatic provinces hosting known major deposits of tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineralisation in Australia, and importantly has also highlighted the potential of several other areas in ‘greenfields’ regions. Results for thirteen areas of the continent with high jor moderate potential (Figure 5.2) are described in the following section.
Figure 5.2 Map showing the potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia. This map has been produced by combining the four mineral systems components discussed in Chapter 4.
5.2 Discussion of prospective regions

5.2.1 Area A: Musgrave Province region

Figure 5.3 Variations in modelled potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineralisation in the region of the Musgrave Province in central Australia.

Within the Musgrave Province the geological units with modelled high potential are:

- Intrusions of the Giles Complex (1052 ± 11 Ma) which is part of the Warakurna Event (ME 50; Thorne et al., 2014)
- Alcurra Dolerite (1067 ± 8 Ma) and Amata Dolerite (820 Ma) which are part of the Warakurna Event (ME 50) and Gairdner Event (ME 52), respectively.

All mineral system components are present with moderate to high values in this region. The highlighted geological units are part of either the Warakurna or Gairdner LIPs and therefore are very favourable in terms of energy sources. Eruptive lavas and swarms of small dykes are not themselves prospective hosts for economic mineralisation: instead the analysis indicates that larger intrusions forming part of the same magmatic events could be prospective.

Table 5.1 Description of the mineral system components for the region of the Musgrave Province.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Moderate in places</td>
<td>High</td>
<td>Varied. Medium to high</td>
</tr>
</tbody>
</table>
5.2.2 Area B: Southern Aileron, Irindina and northern Warumpi Provinces

Figure 5.4 Variations in modelled potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineralisation in the region of the southern Aileron, northern Warumpi and Irindina Provinces.

Within the region of the southern Aileron, Irindina and northern Warumpi Provinces there are a large number of geological units with modelled high to moderate potential. Some of these are listed below:

- Johannsen Metagabbro (1805 ± 3 Ma), Enbra Granulite (1811 ± 3 Ma) and Mount Hay Granulite (1803 ± 5 Ma) which are part of the Mount Hay Event (ME 35).
- Attutra Metagabbro (1786 ± 4 Ma) and Mount Chapple Metamorphics (1774 ± 2 Ma) which are part of the Hart LIP (ME 36).
- Stuart Pass Dolerite (1076 ± 33 Ma) which is part of the Warakurna LIP (ME 50).
- Riddock Amphibolite Member which is undated, but interpreted to be part of the Kalkarindji LIP (ME 57).
- Whistleduck Dyke Swarm, of unknown age and Event attribution.

All mineral system components are present with high favourability in this region. It can be seen that the igneous units of high mineral potential span from the Proterozoic Mount Hay Event (ca. 1810 Ma), to the Cambrian Kalkarindji Event (ca. 510 Ma) (if the Riddock Amphibolite is of this age), indicating multiple periods of mafic magmatism for over 1 billion years. The broad east-west trending belt of enhanced prospectivity coincides with the Desert Bore Shear Zone, Redbank Thrust and Charles River Thrust, giving this region highly favourable lithospheric architecture (Miezitis et al., 2006). The results of the current study largely confirm the qualitative mineral potential analysis of Miezitis et al. (2006). The region of high to moderate prospectivity in the Irindina and southern Aileron Provinces extends beneath cover eastwards towards the southern Mt Isa Orogen and Thomson Orogen.

Table 5.2 Description of the mineral system components for the region of the southern Aileron Province.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>High</td>
<td>High for intrusive rocks</td>
<td>Medium to high</td>
</tr>
</tbody>
</table>
5.2.3 Area C: Kimberley region

Within the region of the Kimberley Province the Hart Dolerite (1790 ± 4 Ma) shows the highest mineral potential. The Hart Dolerite consists of a number of mafic sills that are typically tholeiitic (Griffin et al., 1993) and, with the co-magmatic Carson Volcanics, form part of the Hart LIP. This LIP has been previously identified as prospective for tholeiitic intrusion-hosted Noril’sk style Ni-Cu-PGE deposits (e.g., Hoatson and Lewis, 2014). Several mafic-ultramafic intrusive units in the Halls Creek Orogen, which flanks the eastern side of the Kimberley Province, are modelled with medium to high potential, consistent with the presence of known tholeiitic intrusion-hosted Ni sulfide deposits and numerous prospects in this area (box in Figure 5.5). These include the Savannah deposit (previously Sally Malay), and the Copernicus deposit hosted by the Alice Downs Ultramafics, both within the 1860-1840 Ma Sally Malay Event. Note that volcanic units such as the Carson Volcanics and the widespread Kalkarindji Suite to the east of the Halls Creek Orogen are shown with moderate modelled potential but the volcanics are not prospective in themselves; they are, however, indicative of potential in the co-magmatic intrusive units.

Table 5.3 Description of the mineral system components for the Kimberley Province region.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>
5.2.4 Area D: Pine Creek Orogen and northern McArthur Basin region

Figure 5.6 Variations in modelled potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineralisation in the Pine Creek Orogen-McArthur Basin region, Northern Territory.

Within the eastern Pine Creek Orogen and northern McArthur Basin region, the two geological units with highest mineral potential are:

- Oenpelli Dolerite (1723 ± 6 Ma), part of the Oenpelli Event (ME 38), which intrudes the Katherine River Group in the McArthur Basin (Ahmad et al., 2013), and also occurs within the Nimbuwah Domain of the Pine Creek Orogen (Ahmad and Hollis, 2013).
- Zamu Dolerite, part of the Bow River Event (ME 32), within the Central Domain of the Pine Creek Orogen (Ahmad and Hollis, 2013).

These units form part of a varied group of mostly tholeiitic mafic intrusives and extrusives in this region with a range of ages. They have been highlighted mainly due to high modelled values in both sources of ore constituents and ore depositional gradients. Energy sources are low for all units. The closest LIP is the much younger Kalkarindji LIP to the south. The lithospheric architecture component is also of low favourability, in part reflecting both limited isotopic data and limited deep seismic in this region.

Table 5.4 Description of the mineral system components for the Pine Creek Orogen-McArthur Basin region.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Medium to low</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>
5.2.5 Area E: Mount Isa Orogen

In the region of the Mount Isa Orogen all of the four mineral system components are present. There are two large north-south trending lithospheric structures as well as remnants of the Hart LIP, indicating the involvement of a mantle plume energy source. Among the several mafic to ultramafic units modelled with high potential within this area the Eastern Creek Volcanics (1773 ± 2 Ma) are one of the most prominent. These volcanics are a series of tholeiitic basalts, possibly continental flood basalts, which erupted in a continental rift setting (Glikson et al., 1976; Wilson et al., 1985).

Geochemical analyses of the Eastern Creek Volcanics by Gregory et al. (2008) show an enrichment of Pt, Pd, Au and Cu in the upper Pickwick Metabasalt Member, an enrichment of Au and Cu only in the lower part of the Cromwell Metabasalt Member, and a strong depletion of Pt and Pd in the upper part of the Cromwell Metabasalt Member and in associated doleritic sills. This suggests that chalcophile element contents were elevated in the parent magma, likely due to sulfur unsaturation. Sulfur saturation in the Cromwell Metabasalt Member may have occurred during emplacement (Gregory et al., 2008). Therefore, any intrusive rocks related to the Eastern Creek Volcanics metabasalt members, rather than the volcanics, have high potential for large intrusion-hosted Ni-Cu-PGE sulfide deposits.

Table 5.5 Description of the mineral system components for the region of the Mount Isa Orogen.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>
5.2.6 Area F: Northern Queensland

A number of units are highlighted with moderate to locally high potential in the Georgetown and Coen regions of northern Queensland, including:

- The Chelmsford Gneiss of the 1600–1580 Ma Curramulka Event (ME 42) in the Coen Inlier, and the Cobbold Metadolerite and Lane Creek Formation, both part of the 1665–1645 Ma Lane Creek Event (ME40) in the Georgetown Inlier.

The main contributions to the high modelled potential of these units are favourable lithospheric architecture for the Cobbold Metadolerite, and high values of ore depositional gradients. The Cobbold Metadolerite forms a relatively widespread and abundant intrusive unit in the Georgetown Inlier. The Chelmsford Gneiss is comprised largely of metasediments and contains only subordinate mafic units present as amphibolite and dolerite dykes (of two ages) and also cumulate mafic pods (Bultitude and Rees, 1996). There are a number of related geochemical analyses contributing to high values of the ore depositional gradients component, although the actual relationship between the gneiss and subordinate mafic bodies is not well constrained.

Table 5.6 Description of the mineral system components for the Georgetown and Coen regions.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>High</td>
<td>Medium to Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Figure 5.8 Variations in modelled potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineralisation in the Georgetown and Coen regions of northern Queensland.
5.2.7 Area G: Lachlan Orogen

Geological units with modelled high mineral potential include:

- Micalong Swamp Basic Igneous Complex (430 ± 9 Ma) in the Lockhart Event (ME 60)
- Wambidgee Serpentinite

The Wambidgee Serpentinite is part of the Coolac serpentinite belt which contains small ophiolitic-type podiform chromitite deposits with minor Cu, Au, and PGEs. The ultramafic bodies hosting mineralisation are small elongate bodies, which are interpreted to have formed in back-arc basins. Although much of the Lachlan Orogen is not considered prospective for tholeiitic intrusion-hosted mineral systems due to the predominance of arc-related calc-alkaline and alkaline magmatism, the Micalong Swamp Basic Igneous Complex is tholeiitic in composition and may represent exhumed root zones of an arc. Interestingly there are anomalous thicknesses of inferred mafic rock in the crust in this region (Figure 4.3) coinciding with anomalously thick crust (Figure 4.5) and favourable lithospheric architecture. Small Ni-Cu-PGE sulfide deposits hosted by arc tholeiites are known elsewhere in the world (e.g., Naldrett, 2004; Peltonen et al., 1995).

Table 5.7 Description of the mineral system components for the central-south Lachlan Orogen.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Medium to high</td>
</tr>
</tbody>
</table>
5.2.8 Area H: Gawler Craton

Figure 5.10 Variations in modelled potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineralisation in the region of the Gawler Craton, South Australia. Intrusions of the Gairdner Dyke Swarm are shown as variably coloured lines trending generally northwest in the central-northern part of the Figure.

The principal geological units in this region with elevated modelled mineral potential are:

- Gairdner Dyke Swarm (827 ± 6) which is part of the Gairdner Event (ME 52)
- Myola Volcanics (1791 ± 4) which is part of the Hart Event (ME 36)

Dolerite dykes of the Gairdner Dyke Swarm represent part of the Gairdner LIP, and are probably individually of too small volume to host major Ni-Cu-PGE sulfide deposits. However, as-yet unidentified intrusive bodies feeding the dyke swarm may be highly prospective. The location of the possible causative mantle plume head during the magmatism has been speculated to lie southeast of the Gairdner Dyke Swarm beneath the Adelaide Geosyncline (Zhao et al., 1994). Furthermore, the Little Broken Hill Gabbro in the Curnamona Province may represent an intrusive component of the Gairdner LIP (Wingate et al., 1998). If the supercontinent reconstruction of Li et al. (1995) is correct in linking this part of Australia with southern China, which hosts the ~820 Ma giant Jinchuan Ni-Cu deposit, then the Little Broken Hill Gabbro and affiliated intrusions may be highly prospective.

The area of modelled moderate potential in the eastern Eyre Peninsula corresponds to minor amphibolites within the Myola Volcanics in an area of favourable lithospheric architecture. Based on the age of felsic units in the Myola Volcanics these mafic rocks have been correlated with the Hart
Event (including the Hart LIP), and as such there is a significant contribution to the overall prospectivity from the sources of energy component of the mineral system.

Table 5.8 Description of the mineral system components for the region of the Gawler Craton.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Medium</td>
<td>Medium to low</td>
<td>Medium</td>
</tr>
</tbody>
</table>

5.2.9 Area I: Fraser Zone in the Albany-Fraser Orogen

A northeast-trending zone of high mineral potential has been modelled along the southeast margin of the Yilgarn Craton, corresponding to the Fraser Zone (enclosed within the box in Figure 5.11) within the Albany-Fraser Orogen. The Fraser Zone is a fault-bounded domain measuring approximately 425 km-long and 50 km-wide that is dominated by metagabbroic rocks and lies between Paleoproterozoic basement rocks of the Biranup Zone and Normalup Zone in the Albany-Fraser Orogen (Spaggiari et al., 2013). The Fraser Zone has been interpreted as a structurally modified, lower crustal zone where voluminous gabbroic magmas were variably mixed with contemporaneous granitic magma and country-rock melts (Spaggiari et al., 2013; Hoatson and Lewis, 2014). The main geological unit of high potential for intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia

Figure 5.11 Variations in modelled potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineralisation in the Fraser Zone (box area) of the Albany-Fraser Orogen in Western Australia. Also shown is the southeast portion of the Yilgarn Craton with generally north-northwest trending greenstone belts highlighted.
mineral potential is the Fraser Complex (1291 ± 21 Ma) within the Fraser Event (ME 46). This complex has high mineral potential due to the spatial coincidence of favourable geochemistry and lithospheric architecture along with contributions from the energy source component. The latter component reflects the presence of thick mafic underplating as well as the ~1210 Ma Marnda Moorn LIP (Figure 4.2, Table 4.2), although this occurs mostly to the north of the Fraser Zone. The Fraser Zone hosts the Nova and Bollinger tholeiitic intrusion-hosted Ni-Cu sulfide deposits, discovered in 2012 and 2013, respectively (Figure 5.1). The modelling therefore successfully predicts the belt within which these deposits occur and, importantly, shows this belt to be prospective over a strike length of >300 km, most of which is concealed by sedimentary and regolith cover.

Table 5.9 Description of the mineral system components for the Fraser Zone, Albany-Fraser Orogen.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

5.2.10 Area K: Yilgarn Craton

Within the Yilgarn Craton the geological units with high potential are largely confined to the eastern part, within the Eastern Goldfields Superterrane. Rock types include:
• ultramafic igneous rock (komatiites and related intrusions) which occur across the craton but are concentrated within the Kalgoorlie Terrane,
• high-Mg basalts
• tholeiitic basalts which are very widespread across the craton, and
• layered and more homogenous mafic ± ultramafic intrusions

The prospectivity analysis in the Yilgarn Craton is complicated by the assignment of most mafic and ultramafic rocks within greenstone belts as ‘undifferentiated Archean’ in the Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al., 2014). In particular, although these Archean units contain both extrusive and intrusive components these have not been distinguished within the ‘undifferentiated Archean’ units, nor have they been subdivided by age. One consequence of the lack of subdivision of komatiitic volcanic units from ultramafic (or mafic-ultramafic) intrusive units in this region is that entire greenstone belts have been highlighted in the modelling results as having moderate to high prospectivity (Figure 5.12). If volcanic units had been mapped separately then their prospectivity for intrusion-hosted Ni-Cu-PGE mineralisation would have been modelled as lower than for intrusive units, due to the lower weightings assigned for volcanic versus intrusive components of units and events. The results for the ‘undifferentiated Archean’ greenstone belts in the Yilgarn Craton therefore should be taken to indicate the potential for either or both tholeiitic intrusion-hosted and komatiite-hosted Ni-Cu-PGE sulfide deposits.

Importantly, it is the lithospheric architecture component of the modelling that discriminates greenstone belts with higher and lower prospectivity in the Yilgarn Craton. There are a number of major geological boundaries identified in the architecture datasets of Korsch and Doublier (2015) and Champion (2015), chiefly in the eastern half of the craton, which are responsible for the high prospectivity of greenstone belts in those areas. The high-prospectivity belt extending north-northwest to south-southeast in the central part of the craton contains the highly nickel-mineralised Norseman-Wiluna belt of the Eastern Goldfields Superterrane. Mineralisation comprises komatiite-associated nickel (and lateritic nickel). Notably, the lithospheric architecture has been invoked as one of the major reasons for the density of nickel deposits in this region (e.g., Begg et al., 2010; Barnes and Fiorentini, 2012). These authors have suggested that the lithospheric architecture was a major controlling factor in localising komatiitic melts with upwelling mantle plumes being preferentially channelled away from regions of thicker lithosphere (in the west) to areas of thinner lithosphere (in the east), allowing high volumes of komatiitic magmas into the crust of the Kalgoorlie Terrane. This same lithospheric architecture also may have guided tholeiitic magmas through the crust, via staging chambers. The presence of such intrusive complexes and feeders, which are the potential hosts for intrusion-hosted Ni-Cu-PGE deposits, should not be ruled out within the areas of modelled high prospectivity. More broadly, the potential for magmatic Ni-Cu-PGE sulfide deposits extends into greenstone belts in the far east of the Yilgarn Craton and under cover along the northern margin.

Table 5.10 Description of the mineral system components for the Yilgarn Craton.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>High in Eastern portion</td>
<td>Medium to High</td>
<td>High</td>
</tr>
</tbody>
</table>
5.2.11 Area L: Ashburton region

Figure 5.13 Variations in modelled potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineralisation in the Ashburton region in Western Australia.

The geological units of moderate to high potential in the Ashburton region include:

- The June Hill Volcanics Formation (1799 ± 8 Ma) within the Hart LIP (ME 36), part of the Wyloo Group in the Ashburton Basin.
- Kulkatharra Dolerite (1070 ± 6 Ma) within the Warakurna LIP (ME 50), present as sills within the Edmund and Collier groups (Edmund and Collier basins), e.g., Martin and Thorne (2004).

Units with high potential in this area largely reflect the presence of both Hart LIP and Warakurna LIP magmatism in the region (medium to high favourability for sources of energy component), and the presence of identified crustal breaks (medium favourability in the lithospheric architecture component).

As for other areas with volcanic units highlighted with moderate or high potential, it is the co-magmatic intrusive complexes rather than the volcanics that should be targeted for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineralisation.

Table 5.11 Description of the mineral system components for the Ashburton region.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium to high</td>
<td>Medium</td>
<td>Low</td>
<td>Medium to high</td>
</tr>
</tbody>
</table>
5.2.12 Area M: Pilbara Craton

The geological units of high potential in the Pilbara Craton region are largely confined to the western half of the Pilbara Craton and include:

- Andover Intrusion (3016 ± 4 Ma)
- Millindinna Intrusion (~2925 Ma)
- Munni Munni Intrusion (2925 ± 16 Ma) within the Munni Munni Event (ME 8)

All of these intrusions, which are tholeiitic mafic-ultramafic in composition, host known magmatic Ni-Cu sulfide and PGE mineralisation (Hoatson et al., 1992) and they have been modelled with high mineral potential principally due to their favourable geochemistry. As discussed in the Overview of Results (section 5.1), this is an example where an area of high data density, in this case higher density of geochemical analyses, has contributed to higher prospectivity. Therefore, in order to discover new mineralisation in this area either co-magmatic intrusions should be investigated, potentially undercover, or rocks modelled with lower mineral potential should be followed-up, such as the Cooya Pooya Dolerite. In general, the ‘real’ potential of such units may differ from the modelled results once additional data (e.g., geochemistry) are included in the prospectivity mapping.

It should also be noted that two of the mineral systems components, sources of energy and lithospheric architecture, did not contribute significantly within the Pilbara Craton region, even near the two known tholeiitic intrusion-hosted Ni-PGE sulfide deposits at Mount Sholl and Radio Hill. This is partly due to the fact that digital spatial data for Archean LIPs were not available for this study. Major lithospheric architecture features appear to be poorly defined within the Pilbara Craton based on the available datasets. This could reflect the lack of seismic reflection data as well as the relatively coarse resolution of the AuSREM dataset which is fundamental to some of the datasets mapping lithospheric architecture in this study. Nevertheless, it is interesting to note that the most prospective igneous units highlighted in this study are located close to significant gradients in Nd model age (see Figure 2.7 of Champion, 2013),
which are also consistent with the regional geology. The Nd isotope data therefore may be mapping major crustal domain boundaries that are not strongly evident in other datasets used in the current study.

Table 5.12 Description of the mineral system components for the Pilbara Craton region.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Medium</td>
<td>Medium to high</td>
<td>Medium to high</td>
</tr>
</tbody>
</table>

5.2.13 Area N: Central-north Western Australia

Figure 5.15 Variations in modelled potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide mineralisation in central-north Western Australia.

The geological units of high potential include (from oldest to youngest):

- Mafic and ultramafic rocks correlated temporally with the ~1830-1790 Ma Hart LIP (ME 36) within the Rudall Complex (Tabletop and Connaughton Terranes) of the Paterson Orogen in the northeastern part of Area N (Figure 5.15)
- Glenayle Dolerite (~1066 Ma) and Kulkatharra Dolerite (1070 ± 6 Ma) in the southern part of Area N (Figure 5.15), both part of the Warakurna LIP (ME 50)
- Hasties Gabbro (837 ± 6 Ma) and related Gairdner LIP-aged intrusions in the Paterson Orogen
- Boondawari dolerite and gabbro (508 ± 10 Ma) intruding the northwestern parts of the Officer Basin (including parts of the former Savory Basin), and which form part of the Kalkarindji LIP (ME 57)
All of these geological units with high potential are parts of LIPs, and a total of four LIPs spatially overlap in this region (Figure 4.2). This area also is characterised by thick mafic underplating (Figure 4.3; determined from AuSREM seismic velocity data) which, combined with multiple LIPs, results in a highly favourable sources of energy contribution. Moreover, the region lies at the margins of several crustal blocks, and has strong horizontal gradients in mantle shear-wave velocities that are persistent throughout much of the lithospheric mantle (Figure 4.11). On the other hand, the modelled contributions of the sources of ore metals and ore depositional gradients components of the mineral system are both relatively low with only some small areas of elevated favourability, mainly within the Rudall Complex in the southeastern Paterson Orogen. These low values may partly reflect the lack of geochemical data for many of the mafic and ultramafic units in the region, which are largely concealed by younger basins and regolith. The highly favourable lithospheric architecture and energy source contributions reinforce one another to an extent that dominates the prospectivity results over the relatively low contributions from sources of ore metal and ore depositional gradients.

This region experienced a complex geological history and contains multiple tectonic domains and basins including the Paterson Orogen (Paleoproterozoic to Neoproterozoic), the northwest Officer Basin (Neoproterozoic to Early Cambrian), and multiple intrusive and deformation events (e.g., Grey et al., 2005). A major part of the area shown with high potential in the central part of coincides spatially with the northwestern Officer Basin, which now incorporates most of the former Savory Basin (Williams, 1992; Grey et al., 2005). The sedimentary sequence in this basin is bracketed in time by two LIP events, the Warakurna LIP represented by the Glenayle Dolerite (~1066 Ma), and the Kalkarindji LIP, represented by the Boondawari dolerites and gabbros (508 ± 10 Ma). The basaltic Table Hill Volcanics (504 ± 18 Ma), also correlated with the Kalkarindji LIP, occur within the Middle Cambrian to Devonian Gunbarrel Basin which overlies the Officer Basin in the southeast of Area N.

As part of the Centralian Superbasin, the northwest Officer Basin initially developed across the period of the Gairdner LIP at ~825 Ma. In the Paterson Orogen, the Neoproterozoic Yeneena Supergroup is intruded by the Hasties Gabbro (837 ± 6 Ma) and the Duke Monzonite (835 ± 4 Ma), both dated by U-Pb zircon methods (Maidment et al., 2008). These are age-equivalents of the Gairdner LIP and their presence supports the results of the modelling showing high potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in parts of the Paterson Orogen. Moreover, numerous undated dykes and sills occur within and adjacent to the northwest Officer Basin and have been inferred to be part of either the Gairdner LIP or Kalkarindji LIP (Grey et al., 2005). In the latter case in particular, Kalkarindji-aged magmas feeding intrusions such as the Boondarwari dolerites and gabbros may have had opportunity to interact with sulfate-evaporite-bearing rocks within the Officer Basin. This region of the northwestern Officer Basin is thus considered to have high potential for Noril'sk type intrusion-hosted Ni-Cu-PGE sulfide deposits, and warrants detailed follow-up studies.

<table>
<thead>
<tr>
<th>Sources of Energy</th>
<th>Lithospheric Architecture</th>
<th>Sources of ore constituents</th>
<th>Ore depositional gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>Low to moderate</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 5.13 Description of the mineral system components for central-north Western Australia.
6 Summary and Conclusions

6.1 Method and results

The apparent under-representation of tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia is addressed in this continental-scale study of prospectivity, to assess whether the resource deficit is due to lack of geological endowment or is a consequence of concealment of mineral deposits by sediments, basins and regolith, which have hindered exploration success.

This study is, to our knowledge, the first continental-scale assessment of Ni-Cu-PGE mineral potential of Australia to apply a knowledge-driven GIS-based analysis method. A mineral systems approach is used to identify extensions to known provinces and new mineral provinces in Australia with previously unrecognised potential to host giant or major Ni sulfide deposits. The study does not attempt to identify individual prospective intrusions or parts of intrusions containing the ore deposits themselves. Rather, areas are identified that are considered worthy of follow-up by exploration companies and others to ascertain the presence (or otherwise) of economic mineralisation.

A conceptual model for the formation of tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits, which is based on a review of published studies of major deposits globally, underpins the mineral potential analysis. This model incorporates four mineral system components, namely: (1) energy sources or drivers of the ore-forming system; (2) crustal and mantle lithospheric architecture; (3) sources of ore metals (i.e., Ni, Cu, PGE in the target magmatic systems in this study); and (4) gradients in ore depositional physico-chemical parameters. For each of the four system components 'theoretical' conceptual criteria were developed which represent favourable geological processes for the system components. These in turn are represented by 'mappable criteria' for which proxy geoscientific datasets were developed. Maps of favourability for each system component were created using overlays of rasters that were weighted (fuzzy logic-based) according to the perceived importance, applicability and confidence level of each input dataset in the mineral system analysis. The four component maps were allowed to contribute equally to the final mineral potential map so that the highest potential areas represent targets where there is high favourability for the presence of all four mineral system components.

The GIS analysis of prospectivity uses a wide range of continental- to regional-scale geological, geophysical and geochemical datasets representing fundamentally important geological features in the ore-forming mineral systems. Several of these new datasets have been developed specifically for the mineral potential study.

The results predict high potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in a wide geographical and age range of geological provinces across Australia. The modelling approach was validated by successfully predicting high prospectivities of the districts hosting the few known major intrusion-hosted Ni-Cu-PGE sulfide deposits. These deposits were not included as inputs in the modelling (to avoid biasing the results), although mineral occurrences of Ni and PGE were included.

The major areas with known intrusion-hosted Ni-Cu-PGE deposits, and with high or moderate potential in extensions of the mineralised provinces, are as follows (from oldest to youngest).
• North Pilbara Craton, hosting known PGE and Ni sulfide mineralisation in the Munni Munni and other Archean layered mafic-ultramafic intrusions.

• Eastern Yilgarn Craton, with known Archean komatiitic volcanic-hosted Ni-Cu-PGE sulfide deposits but also with potential for komatiitic, picritic and tholeiitic basaltic intrusion-hosted mineralisation; also potential for both intrusion- and volcanic-hosted Ni-Cu-PGE deposits under cover in the far eastern, southeastern and northeastern margins of the Yilgarn Craton;

• Halls Creek Orogen (northeast Western Australia) including known Ni-Cu-PGE mineralised Paleoproterozoic intrusions in the east Kimberley (e.g., Savannah deposit); also intrusions of the Hart LIP in the Kimberley Province and King Leopold Orogen in the western Kimberley.

• Fraser Zone within the Meso- to Neoproterozoic Albany-Fraser Orogen (southeast Western Australia), hosting known Ni-Cu sulfide mineralisation at the Nova-Bollinger deposits, and under-cover extensions to the northeast;

• Musgrave Province in central Australia, including known mineralised intrusions (Nebo-Babel deposit) in the ~1050 Ma Giles Complex (part of the Warakurna LIP) and extensions of this complex under cover.

Provinces and regions with predicted high to moderate potential with no known major deposits of tholeiitic intrusion-hosted Ni-Cu-PGE sulphides include the following (in approximate age order).

• Southern Aileron Province (Northern Territory and Western Australia), including a series of mostly-concealed Paleoproterozoic intrusions; also units within the Warakurna Event (~1050 Ma); and the Irindina Province and its extensions eastwards under cover, including the Cambrian Riddock Amphibolite (part of the ~510 Ma Kalkarindji Event);

• Ashburton region (northwest Western Australia), where the Paleoproterozoic Hart Event and Mesoproterozoic Warakurna Event are represented as dykes and sill complexes;

• Pine Creek Orogen and northern McArthur Basin (Northern Territory), including the Paleoproterozoic Zamu Dolerite and Oenpelli Dolerite;

• Mt Isa Orogen, where the Paleoproterozoic Eastern Creek Volcanics may represent the eruptive portions of prospective but as-yet undiscovered intrusive equivalents;

• Eastern Gawler Craton and southern Curnamona Province where plutonic equivalents of the Gairdner Dyke Swarm, such as the Little Broken Hill Gabbro, may represent parts of highly prospective intrusive complexes;

• Central-northern Western Australia where four known LIPs have affected the lithosphere from the Paleoproterozoic to the Cambrian, and including the Rudall Complex and intrusions within and adjacent to the northwest Officer Basin;

• Central-southern Lachlan Orogen (New South Wales) and in particular the tholeiitic Micalong Swamp Basic Igneous Complex (~430 Ma), a possible arc tholeiite.

6.2 Limitations of the mineral potential modelling

A number of other regions of the continent show moderate potential in the GIS modelling results, such as the southern and western margins of the Yilgarn Craton (Western Australia), the western Gawler Craton (South Australia), the Georgetown and Coen Inliers (north Queensland), and the Glenelg Zone (western Victoria). Prospective basement in many of these regions lies under cover and in areas where few geochemical data are available in the OZCHEM database, which is spatially biased towards outcrop. It is recognised that additional geochemical data in areas of covered basement rocks
could significantly change the assessment of prospectivity of those areas by better constraining the contributions of the ‘sources of ore metals’ and ‘ore depositional gradients’ components in the mineral system analysis. For this reason the results of the current study are viewed as minimum permissible areas of potential; addition of data in the analysis is likely to have the effect of increasing the areas of potential, particularly under cover. However, this will be counter-balanced by the negative effects of any unfavourable geochemistry as more data are included, including recognition of melt versus cumulate compositions in high-Mg rocks.

The effectiveness of available datasets as proxies for the desired mappable criteria is an issue in any GIS-based knowledge-driven prospectivity analysis. This has been addressed as far as possible by assigning weightings commensurate with the importance and applicability of each dataset in mapping a particular mineral system criterion. Uncertainties in the spatial distribution and resolution of the datasets is incorporated in the ‘confidence’ weightings.

Several of the areas identified with high modelled potential contain volcanic units and yet these extrusive rocks are not themselves prospective for the target deposit type, intrusion-hosted Ni-Cu-PGE deposits. To mitigate this effect the weightings of volcanic-dominated units and events were set lower than the weightings for intrusive-dominated units and events. Exploration targeting therefore should focus on the intrusive co-magmatic equivalents of the volcanic units; the most favourable areas may lie beneath the volcanic units, or laterally, in some cases far from, the preserved areas of volcanic rocks. The possibility of such intrusive equivalents now residing in a different geological province to the volcanics should not be dismissed. An example may be Little Broken Hill Gabbro, a plutonic intrusion (albeit small) in the Curnamona Province that is co-magmatic with the Gairdner Dyke Swarm in the Gawler Craton and equivalents in the Musgrave Province. The temporal framework provided by the Australian Mafic-Ultramafic Magmatic Events GIS Dataset (Thorne et al., 2014) now allows users to extrapolate spatially within particular events of high mineral potential. Further geochronological data for mafic and ultramafic units will greatly enhance the usefulness of this fundamental dataset.

These gaps in data coverage and limitations in the spatial and temporal resolution of some input datasets mean that the results should be used to aid exploration targeting at craton- to regional-scale (rather than deposit-scale) and to identify areas and magmatic events worthy of acquisition of additional data to ground-truth the prospectivity assessment. The study does not attempt to identify individual prospective intrusions or parts of intrusions containing the ore deposits themselves.

In addition to improvements in data coverage and resolution, recommended future work includes: (a) sensitivity analysis of the input datasets, to test the varying effects of different weightings on the results; (b) use of seismic tomographic datasets other than the AuSREM dataset, to better constrain lithospheric architecture particularly within the craton blocks; (c) incorporation of spatial data for the distribution of sulfur-bearing host rocks in the ‘ore depositional gradients’ component of the mineral system analysis; (d) direct use of neodymium isotope data in modelling lithospheric architecture rather than interpreted gradients.
References


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Appendix A GIS modelling workflow and input datasets

A.1 GIS modelling workflow

This GIS-based prospectivity analysis uses a knowledge-driven approach to combine different datasets. The background to the approach is explained in Sections 3.2 and 3.3. Here we describe the workflow in more detail. The approach combines national datasets for each mineral system component (energy sources, lithospheric architecture, sources of ore metals and ore depositional gradients) as rasters with numerical field values representing the data, and applies a weighting value to each raster (determined qualitatively by the authors). The weightings are given in Table 3.2. A 500 m grid was chosen for the GIS modelling because it honours the spatial resolution of the majority of the input data whilst ensuring that the sizes of the datasets (in bytes) are not too large to compute the modelling results at a national scale.

The technical work flow used in the GIS modelling is illustrated in Appendix Figure A.1, commencing on the left side with the input datasets. These correspond to the 'Datasets' column in Figure 3.2. Some pre-processing of raster and vector datasets was required; these pre-processing work flows are illustrated in Appendix Figure A.2 and Appendix Figure A.3.

The Python programming script used to implement the work flow is available on-line (Coghlan, 2015): https://github.com/GeoscienceAustralia/Nickel-Mineral-Potential-Modelling

For example, three datasets were combined for the sources of energy component. Each vector dataset (Appendix Figure A.3) was converted to a raster using the 'polygon to raster' Python script in ArcGIS and then converted to an integer, which creates an attribute table that is populated with the weightings using the 'populate fields' Python script. Converting to an integer multiplies all values within the raster by 1000. The three integers were then combined using the weighted sum (feature weight) Python script which works by multiplying the designated field values for each input raster by the specified weight and then sums (adds) all input rasters together to create an output raster. The output raster was normalised from 0 to 1. The scripts have been written in Python and a tool box has been created to use the scripts in ArcGIS 10.2.

A similar process is used to produce output rasters for the other three mineral systems components (Appendix Figure A.2). The steps taken to create each input raster dataset are explained in detail in the following section, and flow charts illustrate how the rasters are combined to produce the output rasters. The four output rasters for each mineral system component are then combined together using a weighted sum (equal weight) script which executes a weighted sum calculation using an equal weight given to each input raster (i.e., 0.25 for each of the four rasters). The output raster is normalised from 0 to 1 yielding the final map of mineral potential, which shows areas of high potential in shades of red and orange, areas of moderate potential in yellow shades and areas of low potential in blue colours.

The following section details the creation of the individual input datasets in the GIS modelling of mineral potential. For reference to the mappable and theoretical criteria to which these datasets correspond, see Table 3.2.
Appendix Figure A.1 Workflow for GIS processing of data for the mineral potential analysis, showing four groups of paths, each group leading to a map for that component of the mineral system. These are combined into the final output map of mineral potential.
A.2 Energy sources or drivers of the ore forming system

A.2.1 Australian Proterozoic Large Igneous Provinces GIS Dataset

This dataset contains the interpreted extents of five LIPs in Australia (Claoué-Long et al., 2015): Marnda Moorn, Warakurna, Gairdner, Kalkarindji and Hart LIPs. Where the interpreted extent of one LIP overlaps with that of another LIP the polygon is given a higher value, as shown below and in Appendix Figure A.4:

- No polygons – 0
- One polygon – 0.25
- Two polygons – 0.5
- Three polygons – 0.75
- Four polygons – 1
Appendix Figure A.4 The input layer created from the Australian Proterozoic Large Igneous Provinces GIS Dataset, which includes the ~510 Ma Kalkarindji LIP. Higher values occur where polygons overlap.
A.2.2 Geological polygons of LIPs from the Australian Mafic Ultramafic Magmatic Events GIS Dataset

The polygons, points and lines from the Australian Mafic Ultramafic Magmatic Events GIS Dataset (Thorne et al., 2014) that are identified as being part of the five Proterozoic LIPs, Marnda Moorn, Warakurna, Gairdner, Kalkarindji and Hart, have been used to create the input layer shown in Appendix Figure A.5.

A.2.3 AuSREM seismic tomography: Vsv >7.1 km/s above the Moho

The raster shown in Appendix Figure A.6 has a continuum of values from 0 to 1, and represents the mappable criterion: minimum thickness of inferred mafic rocks in the crust. The scientific rationale is explained in Section 4.1.2.2. The raster was resampled to the defined cell size (500 m) and snapped to the same extent as the other rasters.
Appendix Figure A.6 Input raster derived from the AuSREM dataset (Vsv > 7.1 km/s above the Moho), representing the thickness of inferred mafic rocks in the crust mappable criterion.

A.2.4 Weighted sum calculation

These three layers were combined into one layer using a weighted sum (feature weight) script (Appendix Figure A.7). The process involves multiplication of the designated field values for each input raster by the specified weight, and then summing (overlay addition of) all input rasters together to create an output raster.
Appendix Figure A.7 Flowchart showing combination of input layers (A, B and C) to produce an output for the sources of energy component (D), using a weighted sum. The input layers are shown in more detail in the following figures: A) Appendix Figure A.4, B) Appendix Figure A.5, and C) Appendix Figure A.6.
A.3 Lithospheric architecture

A.3.1 AuSREM seismic tomography: horizontal gradients in Vsv

The raster shown in Appendix Figure A.8 has a continuum of values from 0 to 1. As explained in Section 4.2.2.1 the mappable criterion: boundaries of lithospheric blocks is represented in this dataset. It was calculated from the AuSREM velocity model of Kennett et al. (2013a) by summing the horizontal gradient values of the vertical component of the shear-wave velocity ($\Delta V_{sv}$) for a series of depth slices at 50 km vertical spacing, and then averaging these values according to the number of slices present above the lithosphere-asthenosphere boundary. After normalisation, the raster was resampled to the defined cell size (500 m) and snapped to the same extent as the other rasters.

Appendix Figure A.8 The input layer for the horizontal gradients in shear-wave velocity mappable criterion.
A.3.2 Major Crustal Boundaries of Australia

Major crustal domain boundaries are represented by the dataset of Korsch and Doublier (2014). The following values were given to each line in the dataset based on the confidence field:

- None – 0.1
- Low – 0.3
- Medium – 0.6
- High – 0.8

The lines were arbitrarily buffered to 50 km, as illustrated in Appendix Figure A.9.

Appendix Figure A.9 The input raster map of major crustal-scale breaks interpreted from deep seismic reflection and other geophysical and geological data.
A.3.3 Neodymium Isotopic Domain Boundaries of Australia

Major crustal domain boundaries are represented by the map of Champion (2015), which is an interpretation of the boundaries of crustal domains based on neodymium isotope (two-stage depleted mantle) model age data. The following values were given to each line in the dataset based on the confidence field. The lines were arbitrarily buffered to 50 km (Appendix Figure A.10).

- Unconstrained and low – 0
- Medium – 0.4
- High – 0.6

Appendix Figure A.10 The input raster for the major crustal domain boundaries interpreted from neodymium isotope (two-stage depleted mantle) model age data across Australia.

A.3.4 Weighted sum calculation

These three layers were combined into one layer using a weighted sum (feature weight) script. This involves multiplication of the designated field values for each input raster by the specified weight, then summing (adding) all input rasters to create an output raster (Error! Reference source not found.).
Appendix Figure A.11 Flowchart showing combination of the three input layers (A, B and C) to produce an output for the lithospheric architecture system component (D) using a weighted sum. The input layers are shown in more detail in the following figures: A) Appendix Figure A.8; B) Appendix Figure A.9; and C) Appendix Figure A.10.
A.4 Sources of ore metals: Ni, Cu, PGE

A.4.1 ‘Ultramafic’ or ultramafic-mafic’, or ‘mafic-ultramafic’, components of units in the Australian Mafic-Ultramafic Magmatic Events GIS Dataset

Two layers were created using the Australian Mafic-Ultramafic Events GIS Dataset (Thorne et al., 2014). For the first layer, polygons, points and lines were selected using the criterion: bulkComposition = ultramafic OR ultramafic-mafic (Appendix Figure A.12). The second layer was created using the criterion: bulkComposition = mafic-ultramafic (Appendix Figure A.13). The Applicability weighting for the second dataset was assigned a lower value than for the first dataset (Table 3.2) because ultramafic rocks constitute a subordinate component of units identified as ‘mafic-ultramafic’.

Appendix Figure A.12 Geological unit polygons, lines and points designated as ultramafic or ultramafic-mafic (according to bulkComposition field in the Australian Mafic-Ultramafic Magmatic Events GIS Dataset).
Appendix Figure A.13 Geological unit polygons, lines and points designated as mafic-ultramafic (according to bulkComposition field in the Australian Mafic-Ultramafic Magmatic Events GIS Dataset).
A.4.2 Units and events with MgO ≥ 12% from OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset

The layer illustrated in Appendix Figure A.14 was created using the workflow outlined in Appendix B. The selection criterion used was MgO ≥ 12%.

Appendix Figure A.14 Input raster for the dataset of geological units and events containing OZCHEM analyses with MgO ≥ 12%.

A.4.3 Tholeiitic units and events from OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset

This layer was created using the workflow outlined in Appendix B. The selection criterion used was: classification = tholeiitic.

See Figure 4.17 for an image of the input raster.
A.4.4 High chalcophile-element abundances: Ni – from OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset

The layer shown in Appendix Figure A.15 was created using the workflow outlined in Appendix B. Reflex logas™ software was used to contour data on plots of MgO vs Ni and to select analyses at and above the 95th percentile. The geological units and events within which these OZCHEM analyses are situated were then selected and weighted according to the dominant presence (or otherwise) of mafic intrusives.

Appendix Figure A.15 Input raster of the dataset for the high abundance of Ni (≥95th percentile).
A.4.5 High chalcophile-element abundances: Cu – from OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset

This layer (Appendix Figure A.16) was created using the workflow outline in Appendix B. The selection criterion used was as follows:

Cu ≥ 180 ppm (90\textsuperscript{th} percentile and above).

\textit{Appendix Figure A.16 Input layer of the dataset for the high abundance of copper (≥90\textsuperscript{th} percentile).}
A.4.6 High chalcophile-element abundance: PGE – from OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset

The layer shown in Appendix Figure A.17 was created using the workflow outline in Appendix B. The selection criterion used was:

\[ \text{Pt} \geq 10 \text{ ppb or Pd} \geq 10 \text{ ppb.} \]

Appendix Figure A.17 Input raster of the dataset for the high abundance of PGEs (Pt \(\geq 10\) ppb or Pd \(\geq 10\) ppb).

A.4.7 Weighted Sum Calculation

There are multiple theoretical criteria for the sources of metals component (three) and multiple mappable criteria (seven) with corresponding datasets (Table 3.2). A weighted sum (feature weight) calculation was performed on the groups of layers in each theoretical criterion, as follows (Appendix Figure A.18). The three dataset layers representing moderate to high degrees of partial melting were combined into one layer using a weighted sum (feature weight) script and then values divided by three. The high chalcophile-element abundances layers were also combined into one layer using a weighted sum (feature weight) script and then values divided by three. The two resulting layers are then combined with the layer of mafic rocks classified as tholeiitic using a weighted sum (equal weight) script which summed (added) all input rasters together, giving each equal weight (maximum 0.333).
Appendix Figure A.18 Flow chart showing how the input layers were combined to produce an output for the sources of metals component. A weighted sum (feature weight) calculation is performed on the input layers (A-G) for each theoretical criteria. The resulting layers (H-J) are then added using a weighted sum (equal weight) calculation to give the output raster (K). The input layers are shown in more detail in the following figures: A) Appendix Figure A.12; B) Appendix Figure A.13; C) Appendix Figure A.14; D) Figure 4.17; E) Appendix Figure A.15; F) Appendix Figure A.16; and G) Appendix Figure A.17.
A.5 Ore depositional gradients

A.5.1 Chalcophile-element depletions: Ni – from OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset

The layer shown in Appendix Figure A.19 was created using the workflow outlined in Appendix B. Reflex logas™ software was used to contour data in plots of MgO versus Ni and to select samples with values at or below the 5th percentile.

Appendix Figure A.19 Input layer representing mafic-ultramafic units and events depleted in Ni (≤ 5th percentile).
A.5.2 Chalcophile-element depletions: Cu – from OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset

This layer (Appendix Figure A.20) was created using the workflow outline in Appendix B. The selection criterion used was

Cu ≤ 10 ppm
A.5.3 Chalcophile-element depletions: PGE – from OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset

The layer illustrated in Appendix Figure A.21 was created using the workflow outline in Appendix B. The selection criterion used was

Pt ≤ 1 ppb OR Pd ≤ 1 ppb

Appendix Figure A.21 Input layer representing mafic-ultramafic units and events depleted in the PGE (Pt ≤ 1 ppb or Pd ≤ 1 ppb).

A.5.4 Sulfur-saturated igneous rocks – from OZCHEM and Australian Mafic-Ultramafic Magmatic Events GIS Dataset

This layer was created using the workflow outline in Appendix B. The selection criterion used was

S ≥ 1540 ppm

See Figure 4.22 for an image of the input raster.
A.5.5 National Geochemical Survey of Australia PC3 component

The map of the Principal Component Analysis 3 (PC3), from de Caritat and Grunsky (2013), has been joined to the river catchment areas (McPherson et al., 2011). The following values were given to the catchment polygons according to the PC3 results:

- Negative values – 0 (assumed to be non-mafic)
- Positive values – normalised from 0 to 1

See Figure 4.23 for an image of the input raster.

A.5.6 Nickel and PGE mineral occurrences (MINLOC Mineral Occurrences Database)

All mineral occurrences (not deposits) with the commodity ID: Ni and/or Pt and/or Pd and/or Os and/or Ir and/or PGE as the first listed commodity were selected from Geoscience Australia’s mineral occurrences (MINLOC) database. Point locations were buffered with an arbitrary radius of 1.5 km. The locations of these mineral occurrences are shown in Figure 4.24.

A.5.7 Bouguer Anomaly Gravity Grid of Australia

This raster from Bacchin (2009) has a continuum of values from 0 to 1. The raster was resampled to the defined cell size (500 m) and snapped to the same extent as the other rasters. The grid was also clipped to the coast line.

See Figure 4.25 for an image of the input raster.

A.5.8 Total Magnetic Intensity (TMI) Grid of Australia

The data used for this layer (Nakamura and Milligan, 2015) are within ± 4 standard deviations of the mean value of the total magnetic intensity for the map area. This raster has a continuum of values from 0 to 1. The raster was resampled to the defined cell size (500 m) and snapped to the same extent as the other rasters. The grid was also clipped to the coast line.

See Figure 4.26 for an image of the input raster.

A.5.9 Weighted Sum Calculation

There are multiple theoretical criteria for the depositional gradients component (five) and multiple mappable criteria (seven) with corresponding datasets (Table 3.2). A weighted sum (feature weight) calculation was performed on each group of the input dataset layers for each theoretical criterion. Accordingly, the three datasets representing chalcophile-element depletion were combined into one layer using a weighted sum (feature weight) script and then divided by three. This layer was then combined with the layers from the other theoretical criteria using a weighted sum (equal weight) script that summed (added) all input rasters giving each equal weight (maximum 0.16) (Appendix Figure A.22).
A.6 Final Result

The output layers produced for each mineral systems component (described above) were combined using a weighted sum (equal weight) script to yield the final map of potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits (Appendix Figure A.23). Shades of red and orange represent high potential, yellows represent moderate potential, and shades of blue represent low potential.
Appendix Figure A.22 Flow chart showing how the input layers were combined to produce an output for the ore depositional gradients component. A weighted sum (feature weight) calculation is performed on the input layers for each theoretical criteria. The resulting layers are then added using a weighted sum (equal weight) calculation to give the output raster (J). The input layers are shown in more detail in the following figures: A) Appendix Figure A.19; B) Appendix Figure A.20; C) Appendix Figure A.21; D) Figure 4.22; E) Figure 4.23; F) Figure 4.25; and G) Figure 4.26.
Appendix Figure A.23 Flowchart showing synthesis of the four component layers, energy sources (A), lithospheric architecture (B), sources of ore metals (C), and ore depositional gradients (D), using a weighted sum (equal weight) to produce the final prospectivity map (E) of tholeiitic intrusion-hosted Ni-Cu-PGE deposits.
A.7 References


http://dx.doi.org/10.4225/25/550F880BA5AF1


http://dx.doi.org/10.4225/25/54125552CDA7C
Appendix B Workflow for geochemical datasets

B.1 Workflow to create geochemical input layers

Important contributing datasets for the ‘sources of ore metals’ and ‘ore depositional gradients’ components of the modelling utilised whole-rock geochemistry were as follows: units and events with MgO ≥ 12%; mafic rocks classified as tholeiitic; sulfur-saturated igneous rocks; units and events enriched in Ni, Cu and PGE or depleted in Ni, Cu and PGE. These input datasets were created using the following sources of information:

- OZCHEM National Whole-rock Geochemistry Dataset (Champion et al., 2007);
- The Australian Mafic-Ultramafic Magmatic (MUM) Events GIS Dataset (Thorne et al., 2014); and
- Geochemical Classification of Mafic to Ultramafic Rocks in Australia GIS Dataset (Champion and Dulfer, 2015).

The combination of data from these three sources has allowed the results of selections of geochemical data from the OZCHEM database to be extended from the sample points that meet the criteria to the mafic-ultramafic stratigraphic units and events within which the selected geochemical sample locations occur. Accordingly, each of the mappable criteria layers comprise five components:

- Point data, buffered to 1.5 km radius, representing the geochemical analyses in OZCHEM that meet the search criteria;
- Intrusive-dominant unit polygons, representing intrusive geological units which are dominated by mafic-ultramafic rocks (based on reported values in the Mafic-Ultramafic Magmatic Events GIS) and have the same unique identifier in Geoscience Australia’s Stratigraphic Names Database (STRATNO unique ID) as the point data;
- Extrusive-dominant unit polygons, representing volcanic units which are dominated by mafic-ultramafic rocks (based on reported values in the Mafic-Ultramafic Magmatic Events GIS) and have the same STRATNO (the Stratigraphic Names database unique ID) as the point data;
- Subordinate unit polygons, representing geological units that contain only subordinate mafic-ultramafic rocks (based on reported values un the MUMC Event GIS) and have the same STRATNO (the Stratigraphic Names database unique ID as the point data; and
- Event polygons, representing mafic-ultramafic event polygons that have the same eventID as the point data.

The geological polygons were split into dominant and subordinate (based on the proportion field) and intrusive and extrusive (based on the environment field) so the geological unit polygons better represent the targeted rock type of intrusion-hosted magmatic nickel sulfides.

Given the increasing uncertainty resulting from extrapolating geochemical point data to larger map volumes (geological unit and, especially the related mafic-ultramafic event), these items were given the following values:
Appendix Table B.1 Values given to each of the components listed above.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffered geochemical sample point</td>
<td>0.6</td>
</tr>
<tr>
<td>Intrusive geological unit where the mafic or ultramafic lithology was dominant</td>
<td>0.6</td>
</tr>
<tr>
<td>Extrusive geological unit where the mafic or ultramafic lithology was dominant</td>
<td>0.3</td>
</tr>
<tr>
<td>Geological unit where the mafic or ultramafic lithology was subordinate</td>
<td>0.15</td>
</tr>
<tr>
<td>Mafic-ultramafic event polygons</td>
<td>0.15</td>
</tr>
</tbody>
</table>

These weightings represent the likelihood that the feature is representing the true geochemistry of the rocks, i.e. from high (0.6) for the buffered geochemical point data, to low (0.15) for the geological polygons belonging to the same event (as the geochemical analysis meeting the search criteria). Mafic-ultramafic magmatic event polygons were given the lowest weighting as geological units within events do not necessarily have any genetic relationship or even causative commonalities to one another. The process is outlined in more detail below. Additional modifications of the weightings for geological units, e.g. on the basis of the proportion of the available analyses for each unit that favourably (or not) met the search criteria, were not attempted.

B.1.1 Point data

To create each layer the Geochemical Classification table of the Mafic to Ultramafic rocks in Australia GIS Dataset was joined to the OZCHEM National Whole-rock Geochemistry Dataset via the sampleNumber field. This allowed the OZCHEM geochemistry point data to be interrogated based on its analysed geochemistry, unit name, region or geochemical classification. Subsequent rules (selection criteria) were then applied to this joined dataset. For example, to create the magnesium-rich layer the following rule – MgO ≥ 12 – was used to query the geochemistry point data. The results of this query (i.e. those analyses that met the rule) were exported as a shape file and given a 1.5 km buffer (SHAPE 1) and a value of 0.6.

Appendix Figure B.1 Workflow to create the point data layer.

B.1.2 Stratigraphic units

The ‘stratigraphic unit’ layers were produced using the ‘relate’ Geodatabase function between The Australian Mafic-Ultramafic Magmatic Events GIS Dataset and the joined OZCHEM National Whole-
rock Geochemistry Dataset and Geochemical Classification of Mafic to Ultramafic Rocks in Australia GIS Dataset (joined in the point data layer step above). A ‘relate’ process, rather than the more simple ‘join’, was used because of the one-to-many relationship between the Geochemistry dataset and the Events GIS Dataset. Prior to undertaking any ‘relate’ calculations, individual layers from the Australian Mafic-Ultramafic Magmatic Events GIS Dataset were first consolidated into one layer. This was undertaken by combining the AusMaficEventPolygons, AusMaficEventLines and AusMaficEventPoints layers. The AusMaficEventLines were buffered at 500 m and the AusMaficEventPoints were buffered to 1.5 km radius. The resultant consolidated layer was then joined to the MUMGeologicalUnit table based on the unitIdentification field and exported as a final shape file (SHAPE 2).

Appendix Figure B.2 Preparation of the Australian Mafic-Ultramafic Magmatic Events (MUM) GIS Dataset before operation of the ‘relate’ Geodatabase function based on stratno and eventID.

The latter final table (SHAPE 2) was then used to ‘relate’ to the joined geochemical table (SHAPE 1) via the relate item stratno. This relationship effectively selects all MUM polygons with the same STRATNO as the individual geochemical analyses selected to create the prior point data layer. The selected unit polygons are then exported as the stratigraphic units. For example, when all the analyses with MgO ≥12 are selected, the geological units with the same stratigraphic numbers as these analysis are also selected (via the relate). It is assumed that the selected geological unit will have similar geochemistry to the geochemical analyses to which they are related. The geological unit layer is then split into three based on whether the mafic component with the unit is either dominant or subordinate (based on values in the proportion field) and extrusive or intrusive (based on the environment field). Where the mafic component was dominant and intrusive it is given a value of 0.6, where the mafic component was dominant and extrusive it is given a value of 0.3, and where it is subordinate a value of 0.15 is given.

B.1.3 Event polygons

The ‘event’ polygons are produced using a similar process to that for the stratigraphic units. The combined and buffered polygons, points and lines from the Mafic-Ultramafic Magmatic Events dataset (SHAPE 2) are related, via the eventID field, to the joined geochemistry-classification layer (SHAPE 1). Note that only defined events are used; accordingly, the undefined Phanerozoic, Proterozoic and Archean events are removed (eventID 2390, 2389 and 2388). This means that when the analyses in SHAPE 1 are selected, the event polygons that have the same eventID as the analyses will also be selected. The selected event polygons are then exported and given a confidence value of 0.15.

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B.2 References


http://dx.doi.org/10.4225/25/552B4B786431D

http://dx.doi.org/10.4225/25/54125552CDA7C
Appendix C – Selection of Ni geochemical data

Method of selection of Ni-enriched and Ni-depleted geochemical analyses

Levels of Ni in magmas are generally positively correlated with MgO contents (and Mg-number), and there is a considerable range in actual Ni contents within and between geological units. As such, identifying magmas with enriched or depleted Ni contents must also take into account, at the very least, the degree of differentiation of the magma. This is typically achievable when dealing with individual magmatic systems but is not straightforward when such systems are considered collectively, such as for regional or national compilations of whole rock geochemical data as in the present study. Such regional analysis requires statistical analysis coupled with a number of assumptions and generalisations (such as assuming that Ni content can be universally related to one or two geochemical variables, e.g., MgO), producing a pragmatic (and not totally representative) result. Inspection of the available geochemical data has shown that there was a reasonable positive correlation between log MgO and log Ni.

The identification of outliers of Ni geochemical values (both enriched and depleted) was based on the observed positive correlation between log MgO and log Ni. Assuming a linear relationship, a linear regression was calculated using a least squares method with a robust analytical approach. This was undertaken (using Reflex logas™ software) using the least median of squares methodology (Rousseeuw and Leroy, 1987). This aims to minimise the median value of the squared residuals (as against the more typical non-robust minimising of the sum of the squared residuals), thereby minimising the effects of outliers. The method also identifies outliers which can be ranked by their standardised residual values. The method as used in Reflex logas™ is to select the minimum median of the squared residuals from an iterative series (in this case 3000 iterations) of random selected subsets of a specified size (in this case 1000 analyses). For each subset a linear regression equation is calculated from which the squared residuals for the whole group are calculated, and the regression equation with the lowest median residual is taken as the accepted regression. The subsequent residuals calculated for each sample are weighted (0 or 1) depending on whether they have a standardised residual (residual/S where S=robust estimate of the standard deviation of the residuals) of more than or less than 3. Values with a weighting of 1 are then used to recalculate S (S*), residuals are then reweighted (as before though now using residual/S*). Remaining samples with a weighting of 1 are then used to calculate a final least-squares regression equation (given below) as well as final residual values. These data can then be used to identify and define outliers. For the Ni datasets threshold standardised residual values of 4 (i.e. 4 times greater than the standard deviation of the residuals) values have been used to identify samples that have Ni contents greater than expected (i.e., assumed to have been enriched) and also those with Ni contents less than expected (i.e., assumed to have been depleted).

Note that this approach does not discriminate between the varying possible reasons for Ni enrichments/depletions. Also the approach adopted here (for pragmatic reasons) effectively treats all the data together, and not on a geological unit by unit basis for which such Ni enrichments/depletions should ideally be identified (given the range of variables that effect Ni behaviour), and which would result in a series of MgO-Ni magmatic evolution trends. This and the large threshold standardised
residuals, indicate that there may be many enriched or depleted samples not being recognised. Finally it is, not surprisingly, evident from inspection of the calculated regression line that the total population is not behaving linearly (despite the reasonable coefficient of determination value of 0.88). The largest misfit is for elevated MgO values, most probably corresponding to those compositions where the variation is controlled by olivine alone (and not olivine and other minerals). This corresponds to an inflection evident on an MgO versus Ni plot between 12.5 and ~18% MgO. Notably, dividing the geochemical data into two groups (<18% MgO, and >18%), and rerunning the regression analysis makes very little difference to the number of identified upper and lower outliers (total = 346 versus 350). For this reason, the results of only a single population regression were used. Actual parameters from the statistical run using Reflex logas™ are as follows.

7364 Rows, 3000 iterations – sample size 1000

\[ \text{LOG(NI\_PPM)} = (1.857 \times \text{LOG(MGO\_PCT)}) + 0.418 \]

\[ R^2 = 0.8829, \text{ Adjusted } R^2 = 0.8829 \]

Dev=4

3000/1000

346 outliers: 239 lower outliers; 107 upper

C.1 Reference