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Reducing subjectivity in multi-commodity mineral prospectivity analyses: Modelling the west Kimberley, Australia

Mark Lindsay [a,*], Alan Aitken [a], Arianne Ford [a,b], Mike Dentith [a], Julie Hollis [c,d], Ian Tyler [c]

[a] Centre for Exploration Targeting, The University of Western Australia, 35 Stirling Hwy, Crawley, WA 6009, Australia
[b] Economic Geology Research Centre, James Cook University, Townsville, Queensland 4814 Australia
[c] Geological Survey of Western Australia, 100 Plain Street, East Perth, WA 6004, Australia
[d] Geology Department, Ministry of Mineral Resources, Imaneq 1A 201, 3900 Nuuk, Greenland

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ABSTRACT

Predicting realistic targets in underexplored regions proves a challenge for mineral explorers. Knowledge-driven prospectivity techniques assist in target prediction, and can significantly reduce the geographic search space to a few locations. The mineral prospectivity of the underexplored west Kimberley region was investigated following interpretation of regional gravity and magnetic data. Emphasis was placed on identifying geological structures that may have importance for the mineral prospectivity of the region. Subsurface structure was constrained through combined gravity and magnetic modelling along three transects. Crustal-scale structures were interpreted and investigated to determine their depth extent. These interpretations and models were linked to tectonic events and mineralization episodes in order to map the distribution of minerally prospective regions using a knowledge-driven mineral systems approach. A suite of evidence layers was created to represent geological components that led to mineralization, and then applied to each mineral system where appropriate. This approach was taken to provide a more objective basis for prospectivity modelling. The mineral systems considered were 1) magmatic Ni-sulphide, 2) carbonate-hosted base metals, 3) orogenic Au, 4) stratiform-hosted base metals and 5) intrusion-related base metals (including Sn–W, Fe-oxide–Cu–Au and Cu–Au porphyry deposits). These analyses suggest that a geologically complex belt in the Kimberley Basin at the boundary to the King Leopold Orogen is prospective for magmatic-related hydrothermal mineral systems (including Ni, Au and Cu). The Lennard Shelf is prospective for carbonate-hosted base metals around a feature known as the 67-mile high, and parts of the King Leopold Orogen are prospective for stratiform-hosted base metals. These results show that knowledge-driven mineral system modelling is effective in identifying prospectivity in regional-scale studies of underexplored areas, as well as drastically reducing the search space for explorers working in the west Kimberley.

1. Introduction

Mineral prospectivity modelling is a commonly used technique used to identify areas of high potential to host mineral deposits (Bonham-Carter, 1994a; Carranza, 2009). A wide range of mineral system types can be investigated with mineral prospectivity modelling, from deposit- to continental-scales. Crucially, the aim of these regional analyses is to not necessarily delineate drill targets, but to integrate diverse datasets to map conceptual geological favourability for ore genesis (Hronsky and Groves, 2008; McCuaig and Hronsky, 2000).

Two broad approaches to mineral prospectivity modelling can be taken: data-driven and knowledge-driven. Data-driven approaches use empirical observations of mineralization, usually in the form of spatially located mineral occurrences and deposits to determine their association with various geological features to develop a particular prospective 'signature' of a mineral system. These signatures are then used to identify regions of prospectivity that are not already highlighted by the existing (mapped) mineral deposit or occurrence data. Data-driven approaches rely upon a large dataset of well-described mineralised locations. Data-driven techniques include weights-of-evidence (Ford and Hart, 2013; Porwal et al., 2001), logistic regression (Carranza et al., 2008; Costa e Silva et al., 2012) and neural networks (Nykänen, 2008; Porwal et al., 2004). Conversely, knowledge-driven analyses use conceptual understanding of mineral system components as inputs into modelling (Joly et al., 2012, 2013; Lindsay et al., 2014). Knowledge-driven techniques include fuzzy logic (An et al., 1991; Knox-Robinson and Wyborn, 1997) and evidential belief functions (An et al., 1994a,b). Training data points (e.g., known mineral deposits or occurrences) are not required in knowledge-driven techniques, as the

* Corresponding author.
E-mail addresses: markdlindsay@gmail.com, mark.lindsay@uwa.edu.au (M. Lindsay).

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associations of various components of the mineral system are determined by the operator, as well as their relative importance to the mineralization process.

The mineral systems approach (MSA) (Knox-Robinson and Wyborn, 1997; Wyborn et al., 1994) has been used as a unifying conceptual framework in order to provide a platform for effective exploration targeting methods (Joly et al., 2012, 2013; McCuaig et al., 2010). The MSA recognises that ore deposits are expressions of multi-scale Earth-systems that focus mass and energy flux (McCuaig et al., 2010). Knowledge-driven mineral prospectivity modelling within the MSA framework is especially powerful in greenfields regions where few economic mineral deposit data points are available. Multiple mineral system models are also easily analysed for a given region using knowledge-driven methods (Aitken et al., 2014; Joly et al., 2013), and operators can easily update models and prospectivity maps as new or updated information becomes available. Data ambiguities and a desire for consistency and flexibility in the prospectivity modelling influenced the decision to use a knowledge-driven approach.

The west Kimberley region in northern Western Australia is a greenfields region and ideal for mineral prospectivity modelling using the MSA. Pre-competitive, publically available data have been used exclusively in this study. All relevant information used in developing the mineral systems model in the west Kimberley was extracted from public-domain sources. Geophysical interpretation, which forms a significant basis for many of the geological features used as inputs into the mineral prospectivity maps, was performed using data available from the Geological Survey of Western Australia (GSWA) 'GeoView' internet interface (http://warims.dmp.wa.gov.au/GeoView).

While some publically available mineral occurrence data points are available for this region, they are not considered reliable predictors of economic deposits, and preclude the use of data-driven techniques. The majority of data points in the region are classed as 'occurrences', meaning that concentration values only slightly above background were measured, and not at economic levels. Using such data would be inappropriate for this study as it would only predict other occurrence locations, and not those potentially hosting economic deposits. Further, the reliability of some historical data has been questioned by Hassan (2004), where 'a mountain of tin' reported by A. W. Sergison in the Sunday Times (1908) cannot be attributed to a single source or location. Cross-validation of historical data with locations in public datasets is made difficult due to lack of geographic co-ordinates. The lack of appropriate point and historical data led to the decision to avoid data-driven techniques.

In this contribution, we present prospectivity modelling results using knowledge-driven modelling techniques for a wide-range of generic mineral system types. These are: intrusion-hosted Sn and W; orthomagmatic Ni-sulphide; stratiform-hosted base metals (both volcano- and sedimentary-hosted base metals); porphyry-related and orogenic Au; and carbonate-hosted base metal (Mississippi Valley Type) deposits. We adopt a new approach where a set of prospectivity model inputs are generated, and then applied to each mineral system where appropriate. This is in contrast to similar multisystem studies where a unique set of model inputs are generated for each mineral system. The intended aim in taking this new approach is to reduce the inputs to those that are essential, avoid overfitting the model results, reduce subjectivity, incorporate uncertainty and produce a consistent set of models that reveal realistic areas of prospectivity in the underexplored west Kimberley.

1.1. The geology of the west Kimberley region

The west Kimberley includes the King Leopold Orogen and Lennard Shelf, forming a ~360 km by ~180 km ESE–WNW striking region that separates the southern margin of the Kimberley Basin from the northern margin of the Canning Basin (Fig. 1a). The dominantly Paleoproterozoic King Leopold Orogen can be divided into two distinct tectonic regions: (1) layered mafic and ultramafic sills, I-type granitoid intrusions, metasedimentary rocks, felsic volcanics and migmatites of the Western Zone to the Lamboo Province (Tyler et al., 1995); (2) the deformed sedimentary and mafic volcanic rocks of the Paleoproterozoic Kimberley Basin (Fig. 1a,c). The 1870–1850 Ma Hooper Orogeny, 1835 Ma Halls Creek Orogeny, the <1000–800 Ma Yampi Orogeny and the c. 560 Ma King Leopold Orogeny are recorded in the rocks of the King Leopold Orogen (Griffin et al., 2000; Sheppard et al., 2012; Tyler and Griffin, 1990). The relatively undeformed hills of Frasnian to Famennian (Late Devonian) reef complexes of the Lennard Shelf strike parallel to the southern edge of the King Leopold Orogen (Playford et al., 2009). Reefs surrounded the Neoproterozoic islands of the now Pillara and Oscar Range Complexes. The current day position of the reefs is thought to be controlled by the basement to the Lennard Shelf, considered to be a southward extension of the King Leopold Orogen (Fig. 1c) (Lindsay et al., 2015).

Several rock units are important for mineral prospectivity within the King Leopold Orogen (Fig. 2). The oldest unit is the metaturbiditic Marboo Formation, deposited c. 1872 Ma (Tyler et al., 1999), and the intruding sills of the Ruins Dolerite (Griffin et al., 1993; Tyler and Griffin, 1992). Magmatism related to the Hooper Orogeny is linked to the 1865–1850 Ma Paperbark Supersuite and c. 1855 Ma Whitewater Volcanics (Griffin et al., 2000; Sheppard et al., 1999, 2001). These units form the bulk of the King Leopold Orogen.

The c. 1835 Ma Speewah Group unconformably overlies the northern margins of the King Leopold Orogen and was possibly deposited in a retro-arc foreland basin during the Halls Creek Orogeny (Griffin et al., 1993; Tyler and Griffin, 1992). The c. 1800 Ma Kimberley Group, including the extrusive basaltic rocks of the Carson Volcanics disconformably overly the Speewah Group (Tyler et al., 2006). The c.1797 Ma Hart Dolerite intrudes the Speewah and Kimberley groups forming thick (up to 1.8 km) sills. The Carson Volcanics and Hart Dolerite comprise a large igneous province and cover an area > 160,000 km^2 with an estimated total volume of 250,000 km^3 (Griffin et al., 1993; Tyler et al., 2006). At the western extent of the study is the c. 1740 Ma Wotjulum Porphyry which intrudes the Kimberley Group as a series of sills (Sheppard et al., 2012; Tyler and Griffin, 1992). The youngest rocks examined for mineral prospectivity are the carbonate Late Devonian reef complexes of the Lennard Shelf, which overlie Ordovician rocks, and formed along shorelines of the Kimberley Craton and islands formed by the low-grade metasedimentary rocks of the Oscar Range.

1.2. Existing and possible west Kimberley mineral deposit types

A variety of mineral occurrence types are expressed in the west Kimberley, either as previously mined, sub-economic deposits or as prospects. These include base metal deposits (e.g., Yampi Sound, Grants Find), orogenic Au (e.g., Mount Broome, Robinson River, Oombulgurri), Sn–W (e.g., King Sound), Ni-sulphides (e.g., Camden Sound prospect) and more widely known Mississippi Valley-type Pb–Zn deposits (e.g., Pillara) and diamonds (e.g., Ellendale). The variety of occurrences, deposits and mines recorded in reports (Hassan, 2004) and the GSWA database 'Minedex' indicate the presence of different mineralising systems. While these data sources provide little constraint on the spatial distribution of favourable geological conditions for mineralization, they do provide some guidance in developing mineral system models applicable to the west Kimberley.

1.3. Orthomagmatic Ni sulphide mineralization

Possible orthomagmatic occurrences of Cu and/or Ni are associated with the Hart Dolerite (Lyndon, 1988a) and Noril'sk style, flood basalt-related Ni–Cu–PGE mineralization is suggested by the Australian Mines Atlas (http://www.australianminesatlas.gov.au, Model 5b). A mineral system involving the Hart Dolerite as a source rock and west-northwest trending dykes as fluid pathways was analysed for Ni–Cu–Co mineralization (Hassan, 2004), similar to the Voiseys Bay deposit,

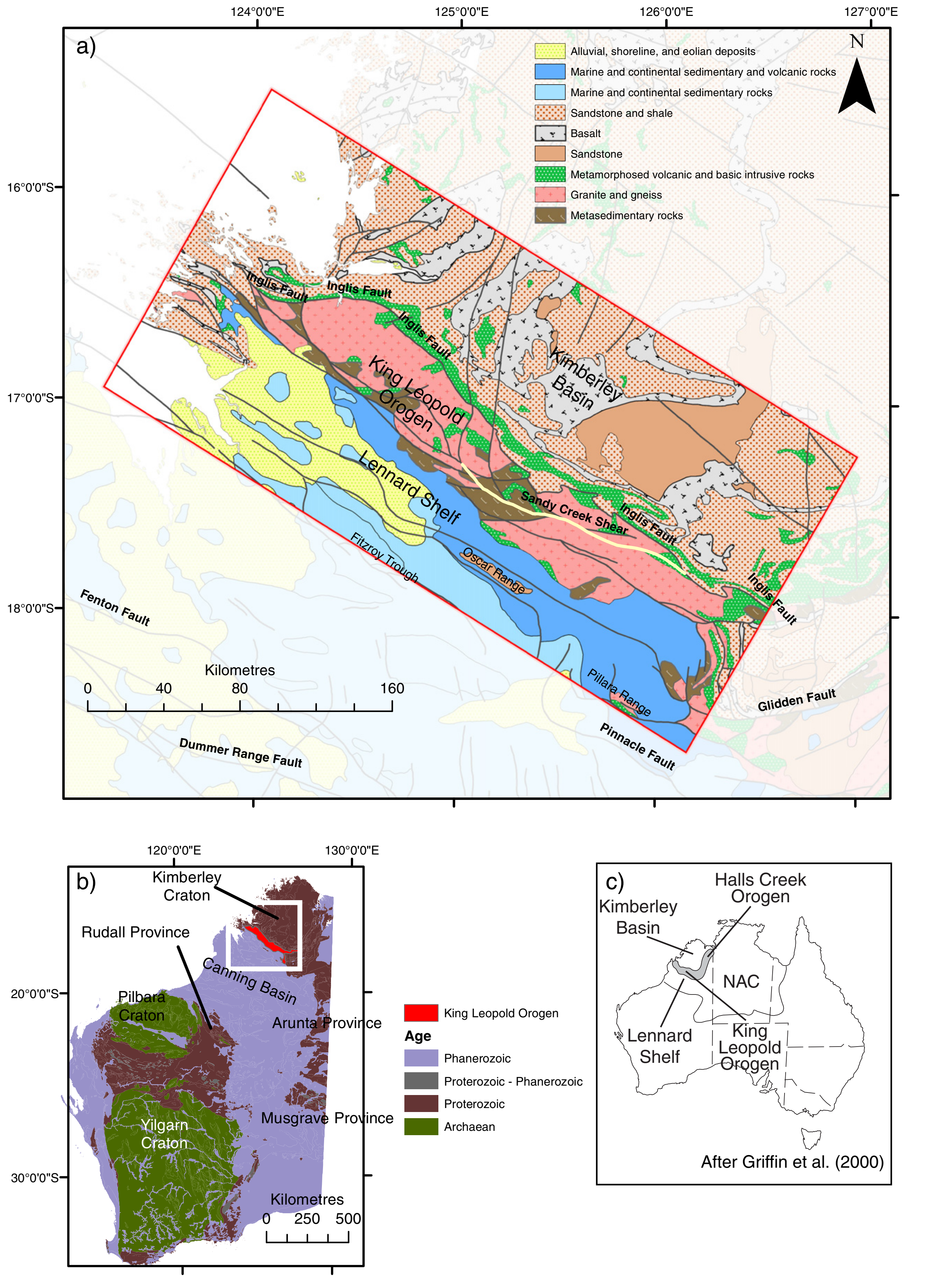

Fig. 1. Location map of the Kimberley Craton and position of the west Kimberley study area. a) GSWA 2.5 m scale solid geology map of the King Leopold Orogen and Lennard Shelf, b) Kimberley region in context of Western Australian tectonic regions, c) components of the North Australian Craton, modified from Griffin et al. (2000).

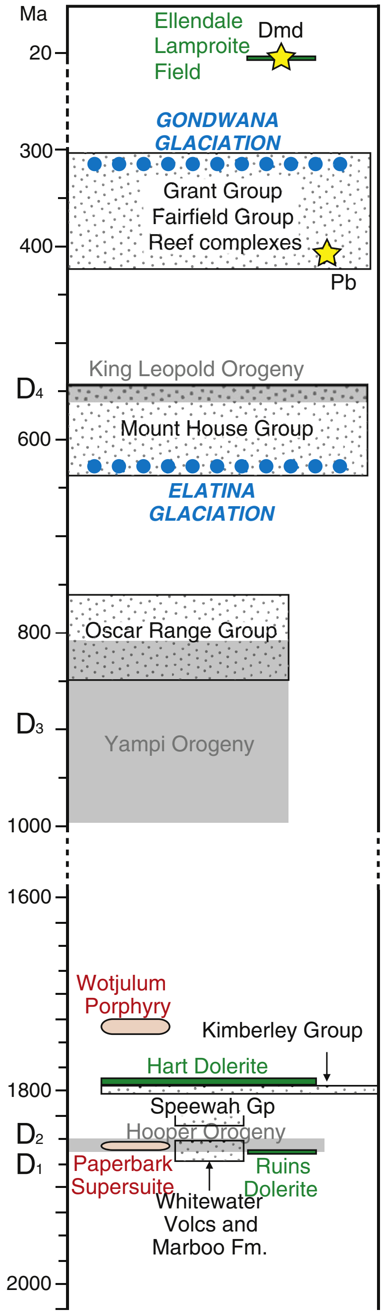

Fig. 2. Time-space plot of important rock units in the western Kimberley shown with their ages and known deposits that are or have been economic.
Modified from Johnson (2013).

Labrador Canada (Naldrett, 1999; Naldrett et al., 1996, 2000) which is a model that places high importance on mafic rocks.

1.4. Orogenic Au mineralization

A large range of Au mineral systems can be broadly labelled under the term orogenic Au and include mesothermal Au, metamorphic Au, Au-only, lode Au, shear-zone hosted and structurally-controlled Au deposits (Groves et al., 1998). The western Kimberley Basin has the potential to host structurally-controlled Au deposits at intersections of north-, northeast- and northwest-trending faults (Garlick, 2003; Striker Resources NL, 2002b,c). Known Au mineralization in the western Kimberley Basin exhibits argillic and hematitic alteration and is observed in quartz veins (Striker Resources NL, 2002a). Au occurrences in the Paperbark Supersuite suggest that the King Leopold Orogen contained desirable components for Au mineralization. The presence of granites, re-activated magmatic fluid pathways and deformation zones proximal to deep-penetrating crustal-scale faults indicates potential for significant deposits.

1.5. Stratiform-hosted base metal mineralization

Stratiform-hosted base metal (SHBM) deposits include a wide variety of proposed genetic models (Lyndon, 1988a,b). SHBM deposits are a major source of Cu, Zn, Pb, Ag and Au, and host a range of secondary elements including Sn, Cd, Sb and Bi (Lyndon, 1988a; Robb, 2007). SHBM deposits can occur within volcanic or volcanoclastic rocks (e.g., volcanic hosted massive sulphide or "VHMS"), however similar systems can also be found in marine sedimentary rocks such as shales, greywackes and turbidites (e.g., sedimentary exhalative or "SEDEX") leading to the broader definition we use here (Lyndon, 1988a). Preferred tectonic environments for VHMS tend to be around plate margins and at major lithospheric boundaries (Sawkins, 1976; Sillitoe, 1973), such as mid-ocean ridges or spreading back-arc basins, island arcs, continental margins, intra-plate oceanic islands and within Archean greenstone belts (Lyndon, 1988a). Faults are important fluid conduits in SEDEX deposits, however deep crustal structures are not critical as mantle-sourced fluids are not required in this mineral system. Carbonate rocks have an association with some VHMS deposits and we include these as a chemical trap (Lyndon, 1988a,b; Robb, 2007).

Some occurrences exhibiting VHMS-style characteristics exist in the west Kimberley, but no mines are currently in operation. Occurrences of Cu–Pb–Zn with the variable presence of Ag, Au or As are found in gossans or laminated graphitic siltstones within the Marboo Formation (Hassan, 2004).

1.6. Carbonate-hosted base metal mineralization

Mississippi Valley-type (MVT) Pb–Zn deposits are the dominant carbonate-hosted mineral systems in the west Kimberley and are found on the Lennard Shelf (Hassan, 2004). Most known occurrences are found in platform, reef, fore-reef and shelf carbonate facies units (Lyndon, 1988b). Temporo-spatial separation is evident as mineralization in the southeast is hosted in older Frasnian limestone rocks, whereas in the northwest mineralization is hosted in younger Fammenian limestone (D'Ercole et al., 2000). Most MVT deposits in the Lennard Shelf are proximal to fault-related dilation zones (Dörling et al., 1996). A combination of fluid flow models, including compaction-driven fluid flow, episodic dewatering from overpressure and seismic pumping, are applicable to the Lennard Shelf MVT mineral system (Dörling et al., 1995). Pb-isotope data suggest that fluids have been transported to the Lennard Shelf from the Fitzroy Trough (Vaasjoki and Gulson, 1986). Faults have focussed fluids from high pressure zones like the Fitzroy Trough, to zones of low pressure at the edge of the basin, basement highs and fault dilation zones (D'Ercole et al., 2000; Dörling et al., 1996).

1.7. Intrusion-related base metal mineralization

1.7.1. Sn–W

Most Sn–W deposits are spatially associated with granitic magmatism (Eugster, 1985; Ferguson and Bateman, 1912). Mineralization is typically observed within pegmatites, quartz veins, stockwork, or is disseminated and is generally situated toward the apical regions of granitic cupolas (Lehmann, 1990; Wood and Samson, 2000). Australia's historical Sn and W production has mostly been from breccia pipes and skarns associated with late-orogenic, subduction-related granites (Solomon et al., 1994). Sn–W mineralization appears to be complex and models require multiple stages of mineralization facilitated by a magmatic-hydrothermal continuum (Heinrich, 1990; Landis and Rye, 1974; Roberts et al., 1998; Solomon et al., 1994). The only known Sn–W mineralization

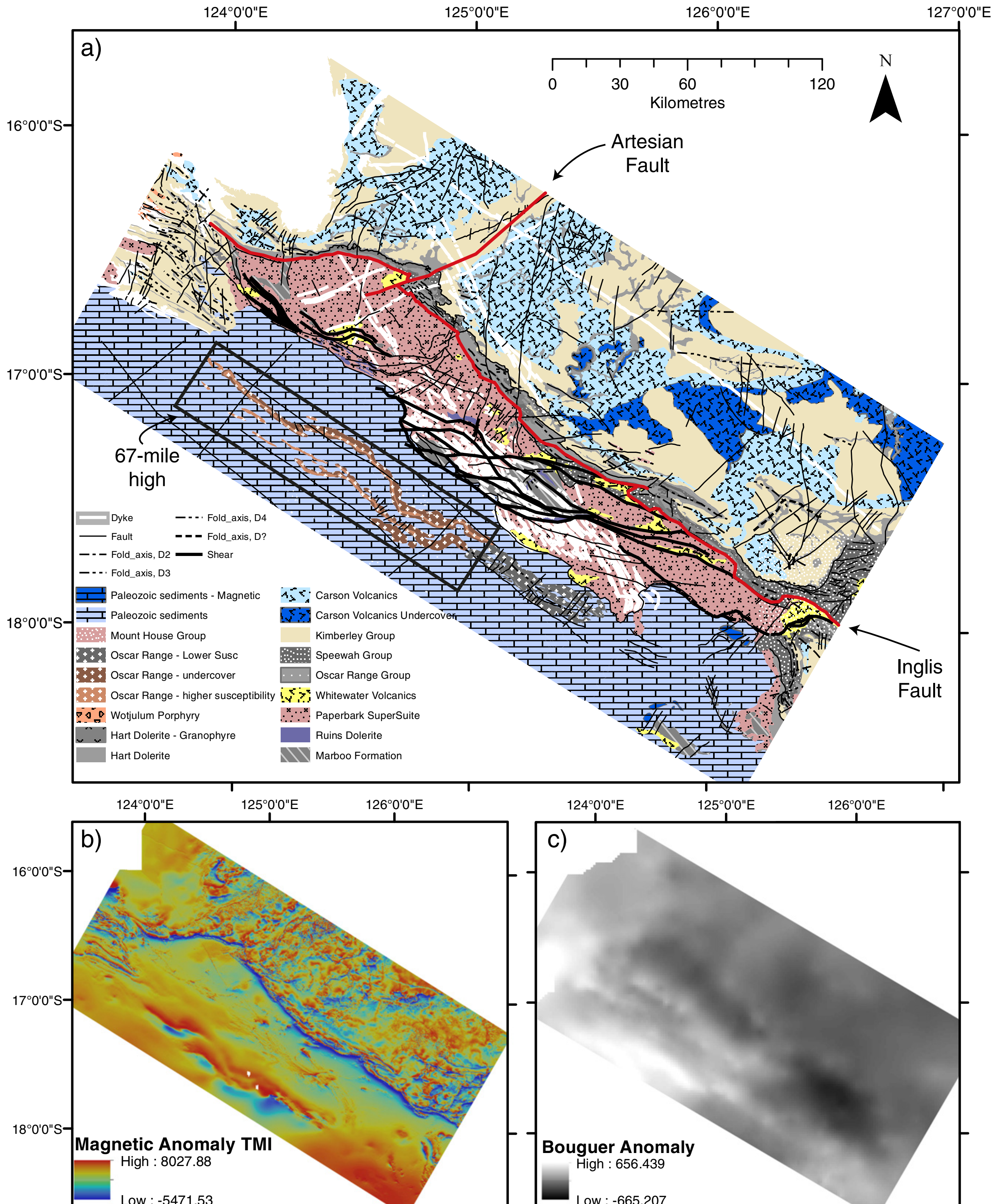

Fig. 3. Structural interpretation from magnetic and gravity data of the west Kimberley (Lindsay et al., 2015). a) Interpreted structure and stratolithological units forming the basis for the prospectivity analysis. Magnetic (b) and gravity (c) data formed the basis for the interpretation. Note the locations of the Inglis Fault, Artesian Fault and 67-mile high (bounded by black outline).

in the west Kimberley is the vein-hosted King Sound occurrence found in the Marboo Formation (Hassan, 2004). The Paperbark Supersuite granites are proximal to the King Sound location suggesting a skarn affinity. A genetic link between mineralization and the granites has not yet been made, nor the extent of fractionation.

1.7.2. Fe-oxide–Cu–Au and porphyry

Intrusion-related base-metal (IRBM) porphyry systems occur as large volumes (10 to 100 km^3) of hydrothermally altered rock centred on an intrusion and include skarn, porphyry and Fe oxide Cu–Au (IOCG) deposits (Sillitoe, 2010). Typical indicators of IRBM porphyry systems are A- and I-type granites, alkaline stocks, and crustal-scale fault zones hosting veins, disseminations, breccias, and massive lenses enriched with polymetallic minerals (Groves et al., 2010). Rock types associated with IRBM are not globally consistent and have broad representation ranges. However potassic and Fe-oxide alteration alongside calcic–sodic regional alteration are commonly associated with IRBM systems. Proximity to craton margins or major lithospheric boundaries has been suggested by Groves and Vielreicher (2001) to facilitate decompression melting of metasomatised mantle, producing volatile-rich alkaline magmas rich in S, Cu and Au. Porphyry systems typically define linear belts and are found at relatively shallow depths (five to 15 km), which leave them susceptible to erosion.

Sporadic exploration over the mid-1800's, 1890–1915 and mid-1960's has yielded little economic Cu, aside from the Yampi Sound Cu mine on the Yampi Peninsula. The Yampi Sound mine is hosted within the Wotjulum Porphyry and proximal to a mineralised fault. IRBM-porphyry mineral systems are arguably one the most studied and understood and their diagnostic features have been known for considerable time (Sillitoe, 2010). Despite limited knowledge of IRBM-porphyry mineral systems in the west Kimberley, prospectivity modelling is supplemented and enhanced with external mineral system analogues.

1.8. Input datasets

The structural and geological interpretation and forward modelling of magnetic and gravity data performed by Lindsay et al. (2015) was used in order to better understand the tectonic evolution and regional-scale structural architecture of the King Leopold Orogen and Lennard Shelf (Fig. 3). Gravity data was used more sparingly than the magnetic data due to lower resolution but was still useful in delineating large-scale domains and structure. Magnetic datasets used for interpretation included total magnetic intensity (TMI), reduction-to-pole (RTP), first vertical derivate (1VD), dynamic range compression (DRC) and combinations of the above with upward continued and residual grids. Gravity datasets used for interpretation were the observed gravity grid, a 1VD and upward continued data. Radiometric data, supplied by the GSWA, was used when confidence was high that outcrop was present. Radiometric data, especially the Th and K band and their ratio was useful in determining possible alteration. Relative timing of geological events was determined from cross-cutting relationships between faults and rock units during interpretation (Table 1).

The deeper parts of the crust were analysed via 2.5D magnetic and gravity forward modelling of profiles 1, 2 and 3 and constrained using rock properties obtained from field samples. Potential basement-penetrating faults are identified. Crustal-scale northeast trending discontinuities likely representing fundamental crustal- to lithospheric-scale boundaries are also interpreted, such as the Artesian Fault (Fig. 3a). The Inglis Fault is also considered to be a deep-penetrating crustal-scale fault due to its wide spatial extent (Fig. 3a) and depth indicated by the forward models (Fig. 4e, profiles 1–3).

1.9. Domains

A series of 'domains' within the west Kimberley are used to simplify geographic reference in this analysis. The southern Kimberley Basin and Lennard Shelf are domains, whereas the King Leopold Orogen is subdivided into the Yampi Fold Belt, Tarraji, Richenda and Elma domains, named after most appropriate proximal GSWA 1:100 000 scale map sheet (Fig. 5).

2. Method: the mineral systems approach to prospectivity analysis

The premise that ore deposits are the focal points of geological process forms the basis for the mineral systems approach (Wyborn et al., 1994). Six key process identified by Wyborn et al. (1994) contributing to the formation of mineral deposits are: (1) a source of energy to start and sustain the mineral system; (2) generation or availability of fluids for metal transport; (3) removal of metal and chemical ligands from appropriate sources; (4) plumbing systems acting as fluid pathways that allow transport of metal-rich fluids to mineral 'traps'; (5) trap regions that modify the composition of fluids allowing metal deposition and (6) preservation of the deposit over time.

The importance of key mineral systems processes changes with the scale of study, as does the ability of the data to adequately image them (McCuaig et al., 2010). This study is at the regional scale, so the most important components are sources, pathways and traps (both chemical and physical) and therefore "predictor maps" are classified into these categories. Generating a prospectivity map from combining predictor maps via a quantifiable and repeatable fashion is achieved through the use of a geographical information system (GIS) and knowledge-driven, "fuzzy logic" modelling techniques.

2.1. Knowledge-driven, fuzzy logic, GIS prospectivity models

Fuzzy logic-based prospectivity modelling requires the creation of predictor maps representing particular geological features of the mineral system that may be prospective for mineralization, for example a set of faults that represent a potential fluid pathway, or a geological unit considered to be a source region (An et al., 1991). To adequately represent each geological feature, the corresponding predictor map is assigned 'membership values' which represent the cell-by-cell weighting of that predictor map in the overall mineral system model. The operator assigns values between 0 and 1 for the map weight, class weight and uncertainty factor, with values closer to 0 representing a poor predictor for the style of mineralization being investigated, and values closer to 1 representing a good predictor. Uncertainty weights are assigned based on the perceived ability of the data to 1) define the feature of interest and 2) image the feature of interest in map form. The perception of reliability is generally low where the data provide an imperfect proxy for the desired prospectivity factor or when it is necessary to interpolate sparse datasets.

Fuzzy logic functions are commonly available as part of both commercial and open-source GIS software, or as a publically available add-on module. The functions are mostly straightforward to execute and are well documented. The simplicity of the approach and its accessibility to the geoscientific community led to the decision use fuzzy logic to perform the prospectivity analysis shown here.

Fuzzy logic prospectivity modelling was performed using the following steps (Joly et al., 2012): (1) identification of mappable proxies for key components of the relevant mineral systems; (2) generation of predictor maps based on these proxies; (3) assigning map weights, class weights and confidence factors to the predictor maps; (4) estimating fuzzy membership values for each predictor map; and (5) generating a prospectivity model after combining weighted predictor maps with an appropriate fuzzy inference network. Current understanding of different mineral systems, their geological characteristics and the tectonic evolution of the west Kimberley are used to assign map and class weights to the fuzzy predictor maps.

A generalised fuzzy model for mineral prospectivity mapping can be defined as follows. If X is a set of n predictor maps X_i ($i = 1$ to n) with r patterns (or classes) denoted generically by x_{ij} ($j = 1$ to r), then n fuzzy sets $\tilde{A}_i$ in X, containing 'favourable indicators for the targeted mineral

Table 1
Summary of events and fault attributes, including field observations attributed to deformation sequence of Tyler and Griffin (1990).

Event	Tyler and Griffin (1990) designation	Tectonic setting	Field description (Griffin et al., 1993; Tyler and Griffin, 1990)	Event code
Pre-Hooper Orogeny (Marboo Formation)	D_1	Extension	Small-scale layer parallel structures in high-strain zones. Extensional shearing and listric faulting at higher crustal levels.	E1
Hooper Orogeny (Whitewater Volcanics, Paperbark Supersuite)	D_2	Compression	Upright folding structures, with NW-trending axes and a moderate to steep plunge. Controlled primarily by shear zones (e.g., Sandy Creek Shear Zone).	C1
Basin formation (Speewah Group)		Compression	Probable deposition with a foreland retro-arc setting (Sheppard et al., 2012).	E2
Basin formation and volcanism (Kimberley Group, Hart Dolerite, Carson Volcanics)		Extension		E3
Yampi Orogeny (Wotjulum Porphyry)	D_3	Compression	Large-scale open folds, shearing on large-scale west-northwest trending structures with south-block-up movement. Sinistral shear on Sandy Creek Shear Zone, dextral shear on northwest-trending splays. Overall south-southwest to north-northeast transport direction. Shear zones partition much of the strain.	C2
Basin formation (Oscar Range, Mount House Group)		Extension		E4
King Leopold Orogeny	D_4	Compression	Large-scale folding with west-northwest trending fold axes Southwest directed thrusting Inglis Fault the basal thrust to D_4 deformation Back-thrusting supported by the presence of high-level structures in the Precipice Fold Belt which indicates ramping of the Inglis Fault.	C3
Basin formation (Phanerozoic clastic and carbonate rocks)		Extension		E5
Basin formation (Fitzroy Volcanics)		Extension		E6

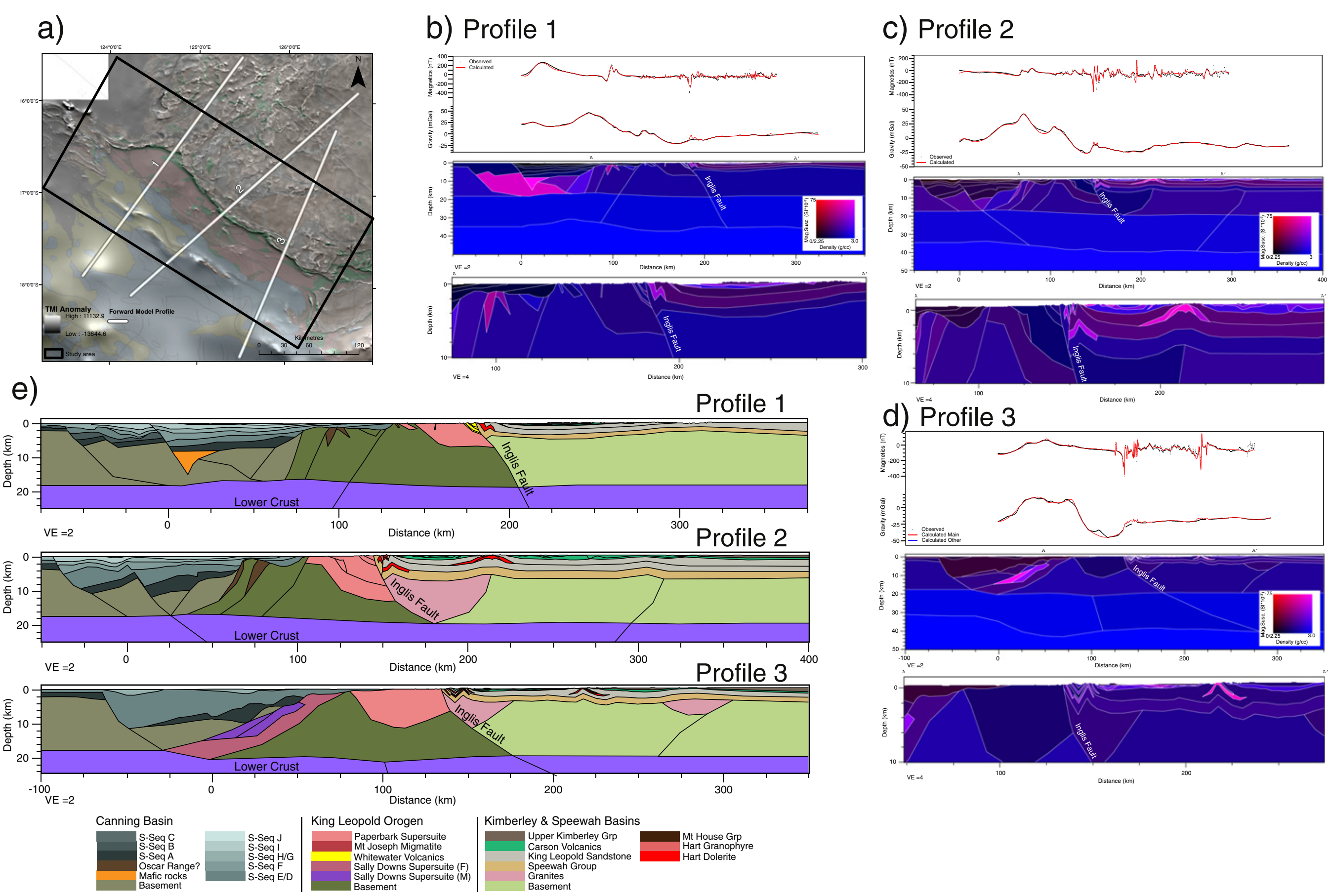

Fig. 4. a) Profile locations of the model sections (b, c, d) of the west Kimberley region (Lindsay et al., 2015). Each profile starts in the southeast; e) geological interpretation of the geophysical forward models. Note the depth of the Inglis Fault, which with its lateral extent supports the supposition that it is a deep penetrating crustal-scale fault.

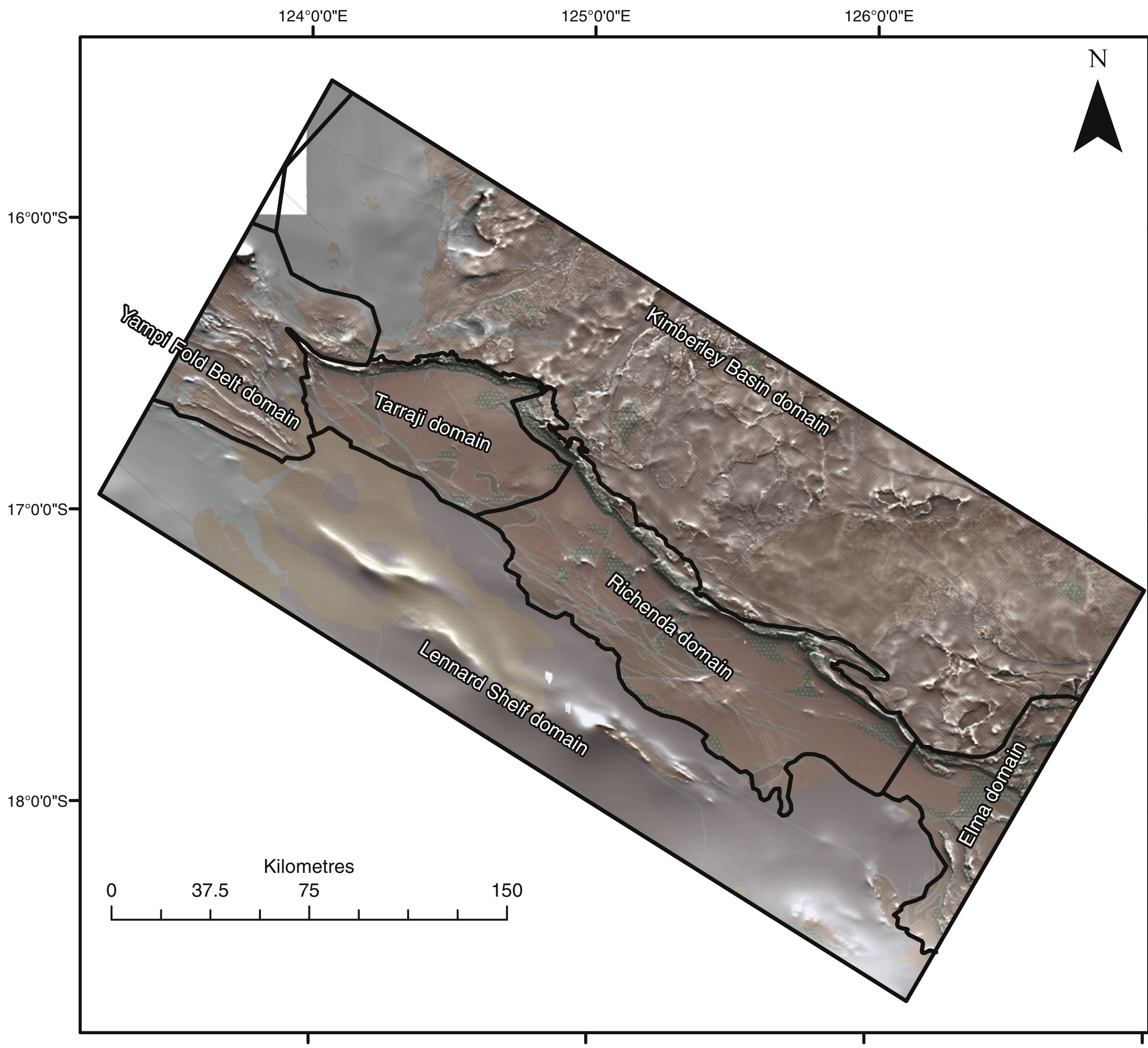

Fig. 5. Domains used for geographic reference.

deposit-type', can be defined as follows (Porwal et al., 2003):

$$\widetilde{A}_i = \left(x_{ij}, \mu_{\widetilde{A}_i} \right) \Big| x_{ij} \in X_i \qquad (1)$$

where μ_{Ai} is the membership function for estimating the fuzzy value of x_{ij} in the fuzzy set $\tilde{A}_i$. The fuzzy membership function can be linear, Gaussian or any other appropriate function. In the present study, we used the following linear function:

$$\mu_{Ai} = m_i \times w_i \times uf_i \qquad (2)$$

where m_i is the map weight, w_j is the class weight and uf_i is the uncertainty factor.

A class of distance-based predictor maps reflect a range of class-weights between 0 and 1 (1 being the most prospective or certain) to reflect decreasing prospectivity with corresponding increasing distance (metres) from the relevant geological feature. Class weight values decrease linearly with distance from the object of interest to edge of a buffer zone that represents the maximum distance permitted to be indicative of prospectivity (Table 2). Areas beyond the buffer zone are assigned a class weight of 0.001. Zero values are not assigned because they are removed when certain operators, such as multiplication ("fuzzy PRODUCT" — see below), are used, resulting in their sometimes unintended removal from the final models.

Each value on a predictor map is a product of the map weight, class weight and confidence factor at each point. The fuzzy predictor maps are then combined using a fuzzy operator appropriate to the

Table 2
Distance buffers assigned to distance-based evidence layers.

Evidence layer	Distance buffer (km)
Pinnacle fault zone	50
Paperbark Supersuite	25
Whitewater Volcanics	25
Wotjulum Porphyry	25
Speewah Group	15
Deep-penetrating crustal-scale faults	10
Basement highs	10
Hart Dolerite	10
Carson Volcanics	10
Other faults	5
Dykes	5
Shear zones	5
Marboo Formation	5
Ruins Dolerite	5
Kimberley Group (not including Carson Volcanics)	5
Jogs	5
Fault intersections	3

component of the mineral system. Various 'operators' are available to facilitate extraction and combination of different predictor maps in a fuzzy logic model (Bonham-Carter, 1994a). These are fuzzy AND, fuzzy OR, fuzzy algebraic PRODUCT, fuzzy algebraic SUM and fuzzy GAMMA. Each performs a different role in emphasising or moderating prospectivity factors (An et al., 1991; Zimmermann and Zysno, 1980) and are described in more detail in Bonham-Carter (1994b) and Raines and Bonham-Carter (2006). Fuzzy AND is a minimising function that finds the values that intersect the input evidence layers and returns the minimum fuzzy values. Fuzzy OR is a maximising function that finds the values in the union of the input evidence layers and returns the maximum fuzzy values. Fuzzy PRODUCT is a penalty-function that returns the product of several fuzzy values which are all less than one. Fuzzy PRODUCT provides a way to combine values without simply returning the value of a dominant set, while strongly penalising input areas with low-fuzzy values. Areas with low fuzzy values have a high inherent uncertainty and should be viewed with caution, especially in greenfields regions where a lack of mineral exploration data is available.

Several different predictor maps were used to represent the processes under which mineral deposits were formed. Table 3 shows how predictor maps were combined in mineral system-specific prospectivity models. A relatively generalised approach to assigning confidence values has been adopted in west Kimberley mineral systems analysis in order to avoid overfitting results and to maintain objectivity. Overfitting occurs when the model is overly complex, and uses more parameters than can be justified by the data. An example of overfitting is a prospectivity model constructed primarily to highlight existing deposits by overweighting features or adding evidence layers that are spatially correlated to the deposit location, but with little justification. While this approach may appear to validate the model as it predicts known deposits, it may also be of little use in giving meaningful and useful results to explorers in greenfields area where prospective geological features exist, but are not highlighted in the final map.

Given the frontier nature of exploration in the west Kimberley, assigning confidence values to each individual predictor map was considered too subjective. Global class confidence values have been assigned to the source (0.9), pathway (0.7) and trap layers (0.5) to avoid excessive bias. While sometimes viewed negatively, some bias is required for knowledge-driven methods. Without bias, a decision could not be made without the data to inform it. Avoiding excessive bias is achieved by finding a balance between making no decision (due to no data), and assigning values to individual evidence layers when such values are only justified in well-explored, data-rich regions. The values assigned to the source, pathway and trap thus represent the decreasing scales at which these model components typically operate, and represent our greater confidence in larger-scale proxies. Fig. 6 illustrates the fuzzy inference network process using the Ni-sulphide model as an example. The layers within the source, pathway and trap classes were combined using fuzzy OR, so the highest values were retained. The final prospectivity models were calculated using fuzzy PRODUCT of the source, pathway and trap predictor maps.

2.1.1. Source

Suspected or known source rocks and/or features containing the necessary elements for the mineral deposit type under study are input to the relevant mineral systems model. Mineralization can form within and at distance from intrusions. A source for sedimentary-hosted and carbonate-hosted systems may or may not be close to the deposit, and may be 10 s to 100 s of kilometres away. To simulate the potential for these distal processes, a series of buffer zones are generated around the border of the objects represented sources, and linearly decreasing values to a given distance from the boundary are assigned.

2.1.2. Pathway

An empirical relationship between ore deposits and major structures and fault corridors has long been recognised (Grauch et al., 2003; Groves et al., 1998; Sillitoe, 2000). Pathways and foci for mineralising fluids are likely to be provided by these structures as zones representing columns of high permeability and low strength (Cox et al., 2001). We used the distance to crustal-scale faults determined from the structural analysis and 2.5D models. We assigned a linear decrease from 0.63 to 0.001 across a 10 km wide buffer zone. The value 0.63 represents the product of a map weight of 0.9 (reflecting importance to the mineral system) and a confidence

Table 3
Inference network for west Kimberley prospectivity modelling. Note that the evidence weight, quoted in bold is the map weight * the confidence weight. For example, the map weight for the deep-penetrating crustal-scale faults (0.9) * pathway confidence (0.7) = 0.63. Event codes listed with faults acting as fluid pathways are defined in Table 1. Refer to Fig. 6 for an example of the inference network operation.

Commodity	Source — confidence weight = 0.9 Evidence layers combined with fuzzy OR	Pathway — confidence weight = 0.7 Evidence layers combined with fuzzy OR	Trap — confidence weight = 0.5 Evidence layers combined with fuzzy OR
All values listed *below* this line are the evidence weights obtained through Eq. (2). Note for distance-based evidence layers, the stated value is the *maximum*, which decreases with distance to the given buffer (Table 3).			
Ni-sulphides	Distance to Hart Dolerite **0.81**	Deep-penetrating crustal scale faults **0.63** Post faults (E4 C2 E5 C3 E6) **0.56** Syn faults (E3) **0.63** Dykes **0.63**	Fault intersection density **0.4** Fault jogs density **0.45** Dyke jogs density **0.45** Alteration index **0.4**
CHBM (Carbonate-hosted base metals)	Distance to Pinnacle Fault system **0.81**	Distance to basement high **0.56** Distance to transfer faults **0.56** Distance to edges **0.56**	*Within* Devonian Limestone **0.4**
Au — 'Orogenic'	Distance to Paperbark Suite **0.72**	Deep-penetrating crustal scale faults **0.63** Post faults (E2 E3 E4 C2 E5 C3 E6) **0.56** Shears, Syn faults (C1) **0.63**	Alteration index **0.4** Competency contrast **0.4** Structural complexity **0.4** Distance to Hart Dolerite **0.45** Distance to Carson Volcanics **0.4** Distance to Marboo Formation **0.4** Distance to Ruins Dolerite **0.35**
Sn–W	Distance to Paperbark Suite 0.72	Deep-penetrating crustal scale faults 0.63 Post faults (E2 E3 E4 C2 E5 C3 E6) 0.56 Syn faults (C1) 0.63	Chemical reactivity 0.4 Alteration index 0.4
Stratiform-hosted base metals	Distance to Marboo Formation **0.72** Distance to Speewah Formation **0.63** Distance to Kimberley Group **0.63**	Post faults (C1 E2 E3 E4 C2 C3 E6) **0.49** Syn faults (E1) **0.63** Basin bounding faults (E5) **0.56**	Organics (Devonian Limestone) **0.4** Alteration index **0.4** Marboo Formation **0.4**
Intrusion Related Base Metals	Distance to Hart Dolerite 0.81 Distance to Ruins Dolerite 0.63 Distance to Paperbark Suite 0.72	Deep-penetrating crustal scale faults 0.63 Post faults (E4 C2 E5 C3 E6) 0.56 Syn faults (E3) 0.63	Distance to Wotjulum Porphyry 0.4 Structural complexity 0.4 Alteration index 0.4

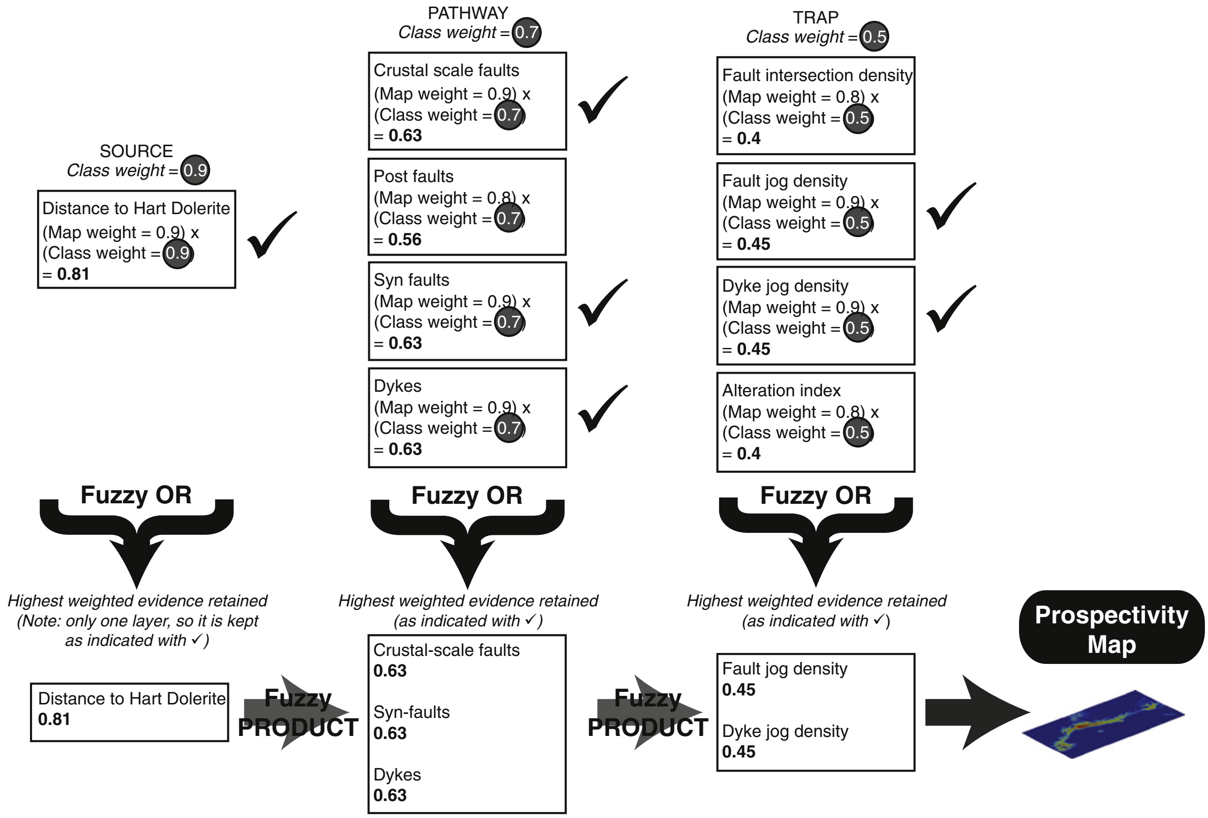

Fig. 6. The operation of a fuzzy inference network, using the Ni-sulphide model as an example. Values are also listed in-text and in Table 3.

weight of 0.7 (reflecting the uncertainty in identifying such structures from geophysical data).

Smaller faults that were considered to be active during mineralization events were assigned a map weight of 0.9, while those post-dating the mineralization event were assigned a map weight of 0.7. These weights are subsequently reduced by a factor of 0.7 via the class confidence weight. These weightings reflect the notion that reactivation events can obscure earlier history, and also can be associated with additional mineralization events. Each fault was attributed to a single tectonic event determined by the geological and geophysical analysis although more prolonged histories are probable for many faults (Table 1).

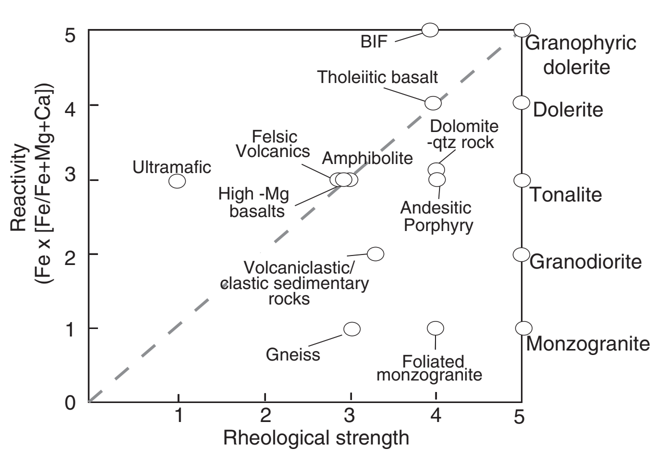

Fig. 7. Relative chemical reactivity and rheological strengths for selected rocks obtained from experimental results.
Modified after Brown (2002).

2.1.3. Chemical scrubbers and physical traps

Chemical and physical processes that initiate the deposition of metals act as mineral 'traps'. A variety of proxies for mineral traps were used.

2.1.4. Fault intersection density, fault jog density and dyke jog density

Localised damage zones on regional faults are considered favourable for focussing mineralising fluid flow in concert with a favourable geochemical environment (Groves et al., 1998; Hagemann and Cassidy, 2000). Damage zones commonly involve large changes in geometry, orientation or continuity and include fault intersections, fault jogs and dyke jogs. The spatial density of these structures over a given area was calculated, then scaled for assignment to fuzzy values where the highest densities where given the highest fuzzy values. The fuzzy values were then used to generate the predictor map.

2.1.5. Alteration index

The alteration index (AI) acts as a proxy for rocks exhibiting indications of alteration from possible hydrothermal activity. The AI is the ratio of potassium content to apparent magnetic susceptibility. Increasing potassium values represent increasing levels of alteration, whereas reduced apparent magnetic susceptibility values represent a common indicator of hydrothermal alteration associated with magnetite becoming oxidised to hematite. Although the inverse (high magnetic susceptibility) can also be an indicator of alteration through oxidation of fayalite to magnetite (Grant, 1985), this is most common in high-grade environments that are not usually prospective for hydrothermal mineralization.

Apparent magnetic susceptibility was calculated using the "FFTSUSC" Geosoft executable within Oasis Montaj. The input was RTP magnetic data and methods using a fast Fourier transform method at 100 m below the data collection surface. Potassium content was

Table 4
Rheological strength and chemical reactivity values used to calculate the competency and chemical contrast predictor maps. Values were obtained from Fig. 7.

Stratigraphic Unit	Rheological strength	Chemical reactivity
Carson Volcanics	4	4
Lennard Shelf limestone	2	5
Lennard Shelf limestone (magnetic)	2	5
Hart Dolerite	5	4
Hart Dolerite–Granophyre	5	4
Lennard Shelf basement	4.5	1.5
Kimberley group	3.2	2
OSCAR range (undercover)	3.2	2
Marboo Formation	3	1
Mount House	3.2	2
Oscar Range	3.2	2
Paperbark Supersuite	4.5	1.5
Ruins Dolerite	5	4
Speewah Group	3.2	2
Whitewater Volcanics	3	3
Wotjulum Porphyry	4	2

obtained from the potassium percentage channel supplied with the radiometric map of Australia (Minty et al., 2009; Savitzky and Golay, 1964). The calculated AI values were scaled for assignment to fuzzy values where the highest AI values were given the highest fuzzy values. The fuzzy values were then used to generate the predictor map.

2.1.6. Competency and chemical contrast

Contacts between geological units with rheological or chemical contrasts are considered favourable trap sites (Groves et al., 2000). Locations with a high physical contrast are prone to repetitive brittle failure (Henley and Berger, 2000; McCuaig and Kerrich, 1998 #559), or shearing (Melling et al., 1988) and these locations routinely exhibit anomalous mineral content. Chemical contrast also acts a proxy for mineral deposition. Reactive rocks interact with sulphide-complexes in fluids, leading to the precipitation of minerals (Groves et al., 1998; Phillips and Groves, 1983). A predictor map was created by assigning to each interpreted lithological unit a relative rheology value (Fig. 7). Each geological contact was attributed with the difference in rheology strength between adjacent units (Table 4). A similar procedure was performed to develop a chemical contrast map. The 'contrast across geological contacts' maps were derived from the rheology or chemical difference of the nearest contact. A line-density tool is used to weight each contact with the contrast weight using a search radius of 3 km. The calculated competency and chemical contrast values were scaled for assignment to fuzzy values where the highest contrast values were given the highest fuzzy values. The fuzzy values were then used to generate the predictor maps.

2.1.7. Structural complexity

Structural complexity is defined as the kernel density of interpreted geological structures within a search radius of 15 km. In contrast to the previous density-based trap measures which only consider one type of structure, structural complexity includes all structures (dykes, shears, stratigraphic contacts and faults). The calculated structural complexity values were than scaled for assignment to fuzzy values where the highest density of structures values were given the highest fuzzy values. The fuzzy values were then used to generate the predictor map.

2.1.8. Distance to or presence within a geological unit

Weights are assigned in linear decreasing value with distance from a geological boundary until a pre-defined distance threshold is reached. Carbonate-hosted base metal (CHBM) deposits are

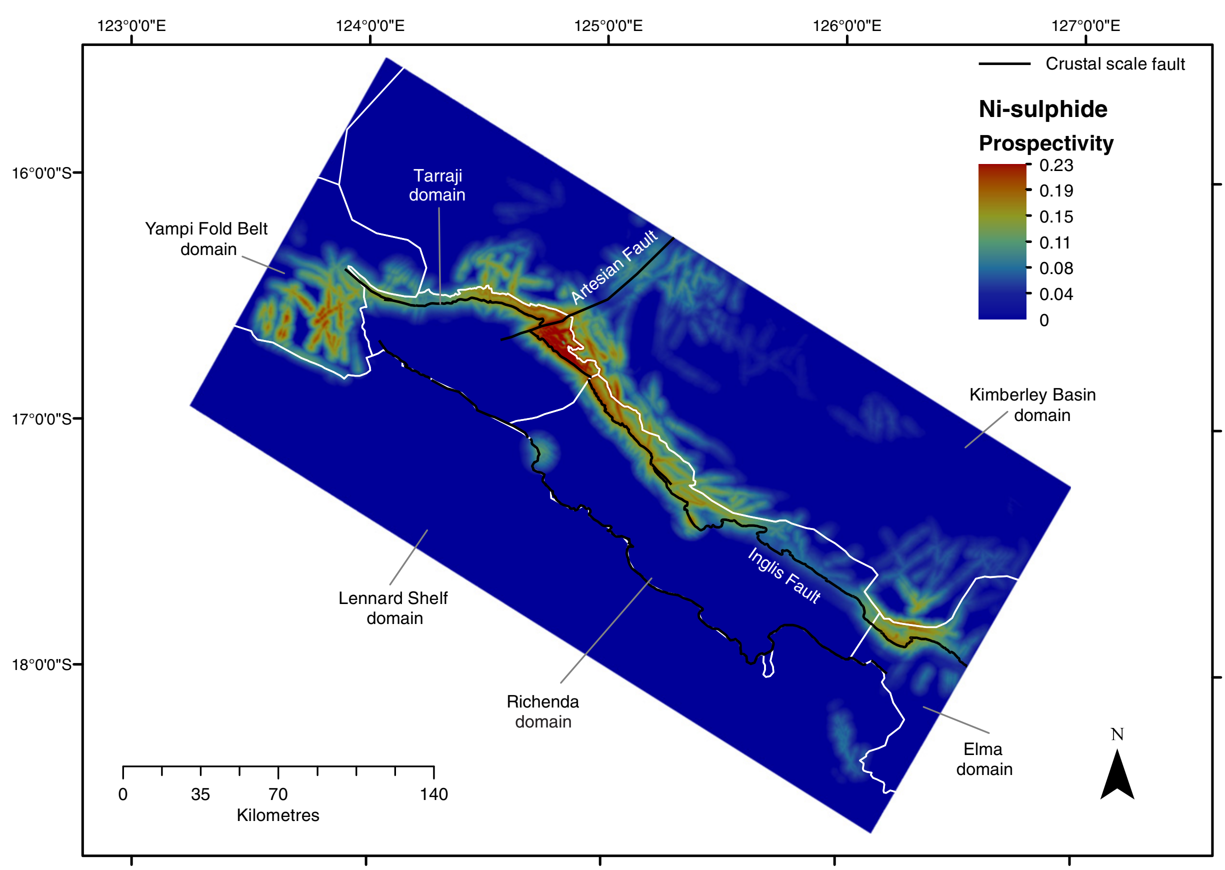

Fig. 8. Fuzzy prospectivity model for the Ni-sulphide mineral system.

different in that the prospective area is constrained to only where the Devonian Limestone is inferred below shallow cover. No buffer or distance weighting was necessary for this predictor map.

2.2. Maintaining objectivity in evidence layer selection

One would hope for a comprehensive dataset in order to develop a mineral system models. As already stated, this is often not the case in greenfields regions, and is no different for the west Kimberley. The advantage of exploring greenfields regions is that the big deposits have not been found yet. The explorer uses a “First Mover” strategy, exploiting the concept that the largest deposits will be found in the earliest exploration phases, or by those who move there first (Hronsky and Groves, 2008).

The approach taken in modelling mineral prospectivity in the west Kimberley acknowledges the lack of available data to support the “First Movers”. The lack of data should not prevent reasonable analysis being performed as long as objectivity in the selection and weighting of inputs can be maintained. Objectivity was achieved by creating a restricted suite of evidence layers from the data supplied by Lindsay et al. (2015) (Table 3). Each evidence layer in the suite represents the same geological elements, irrespective of the mineral system it is being applied to. For example, the same evidence layer representing the Hart Dolerite was used for both the Ni-sulphide and IRBM mineral systems. Evidence layers relevant to the mineral system under analysis were chosen and then weighted according to the class and mineral system they belong to. An additional benefit to using this approach was being able to select an evidence layer and assign it to any class. For example, the Hart Dolerite evidence layer was assigned to the Ni-sulphide and IRBM mineral system source classes, but was also used in the trap class for the orogenic Au mineral system analysis.

3. Results

The following results from prospectivity modelling take into account the interpretations made during the structural interpretation and forward modelling phases of this study. We discuss our rationale for selecting mineral predictor proxies and their weights. Each of the important source, pathway and trap predictor maps is described with weights and confidence values. All the predictor maps and weights for each mineral prospectivity model are shown in the inference network shown in Table 3. For brevity, the combination of map and class weights for a predictor map will be reported in **bold**. For example, “Post faults (**0.56**)” would indicate that the post-faults evidence has been assigned a map weighting = 0.8 and a class (in this case “pathway”) weight of 0.7: (0.8 ∗ 0.7) = **0.56**.

3.1. Orthomagmatic Ni sulphide prospectivity

Inferred pathways for magmatic fluid transport are deep-penetrating faults (**0.63**), syn-magmatic faults (**0.63**) and dykes (**0.63**), and post-magmatic faults (**0.56**). Mineralization trap predictor maps include the fault intersection (**0.4**), fault jog (**0.45**), dyke jog density (**0.45**) and the alteration index (**0.4**) layers.

The most prospective areas in our model for Ni-sulphide mineralization are located within the Tarraji domain near the intersection of the Inglis and Artesian Faults (Fig. 8). Prospectivity is present all along the

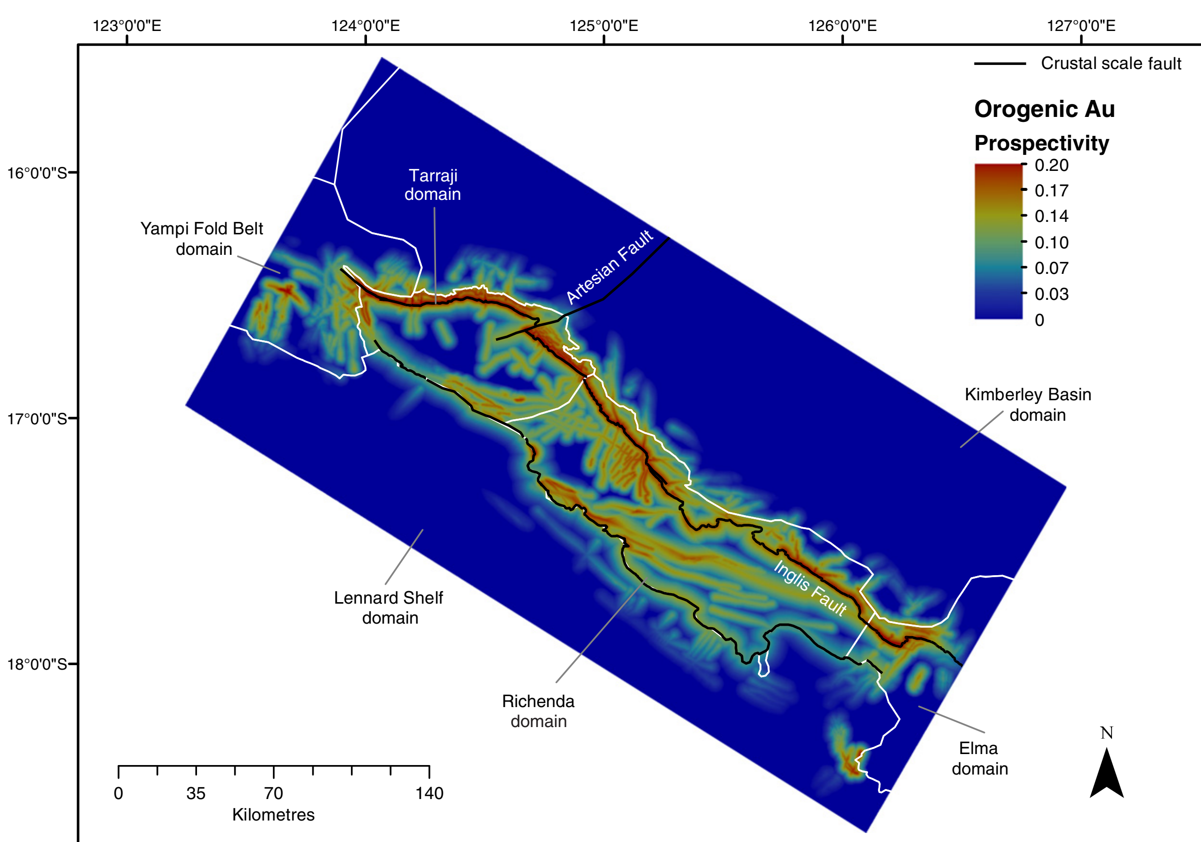

Fig. 9. Fuzzy prospectivity model for the orogenic Au mineral system.

Inglis Fault but decreases with distance, with high prospectivity values also observed in the southern Yampi Fold Belt domain. The Elma domain has some high values in the northeast area adjacent to the Inglis Fault. The interior of the Kimberley Basin is generally not highlighted in this prospectivity analysis due to the lack of locations where Hart Dolerite and dykes/faults are coincident. Some prospectivity may exist at depth in this region, where major structures (e.g., the Phillips Range Anticline) are coincident with Hart Dolerite intrusions and deep seated faults.

3.2. Orogenic Au prospectivity

The most prospective areas in our model for orogenic Au are focussed along the Inglis Fault (Fig. 9). The Yampi Fold Belt domain possesses small regions of high prospectivity in the centre and southwest. Within the Tarraji, Richenda and Elma domains, prospectivity is focused around the margins, but with some high values associated with shear zones trending east-southeast and west-northwest in the Richenda domain. A relatively small region of high prospectivity lies just within the eastern edge of the Lennard Shelf due to the presence of granitoids, Hart Dolerite and Marboo Formation. The dominance of Paperbark Supersuite rocks in the study area has resulted in relatively elevated prospectivity values across the Lamboo Province.

3.3. Stratiform-hosted base metal prospectivity

Potential source rocks have been identified as the Marboo Formation (**0.72**), the Speewah Group (**0.63**) and the Kimberley Group (**0.63**). The siliciclastic Speewah and Kimberley Groups have been included as they represent marine environments. The Speewah Group was possibly deposited in a retro-arc foreland basin during and after the Halls Creek Orogeny (Sheppard et al., 2012), while the Kimberley Basin sediments were deposited in a basin with associated submarine volcanism producing the Carson Volcanics (Gellatly et al., 1970; Plumb, 1981). Mantle-tapping faults are not critical in this mineral system model, however faults in general are still required as fluid pathways. Basin bounding faults (**0.56**) are given a slightly higher weighting to reflect that they are more likely to provide the conduits from which fluids critical to mineralization are transported. Marboo Formation rocks and altered rocks are important evidence for VHMS traps (**0.4**). Carbonate rocks (Devonian Limestone — **0.4**) have been included as a low-weighted proxy for regions hosting marine sedimentary rocks that may indicate proximity to organic-rich rocks typically found in the same environment as hydrothermal sea-floor vents.

Only selected regions of the west Kimberley are prospective for SHBM style mineralization (Fig. 10). The largest modelled zone of high prospectivity is located in the centre of the Richenda domain, with a smaller outlier 20 km to the northwest. The Tarriji and Yampi Fold Belt domains show some prospective regions. Almost all prospective regions are coincident with the Marboo Formation, except the Elma domain which has some above background value regions due to a potential trap of deeper marine rocks.

3.4. Carbonate-hosted base metal prospectivity

The interpreted 'Paleozoic Sediments' unit that includes Devonian carbonates provides the trap for the mineral system. The 'source' of the mineral system is the Pinnacle Fault System to the south of the study area. While obviously not a 'source rock', it is used to represent the transport of mineralising fluids from the Fitzroy Trough. Basement highs, interpreted from extensive, linear magnetic anomalies along the 67-mile high extension of the Oscar Range Inlier have been included

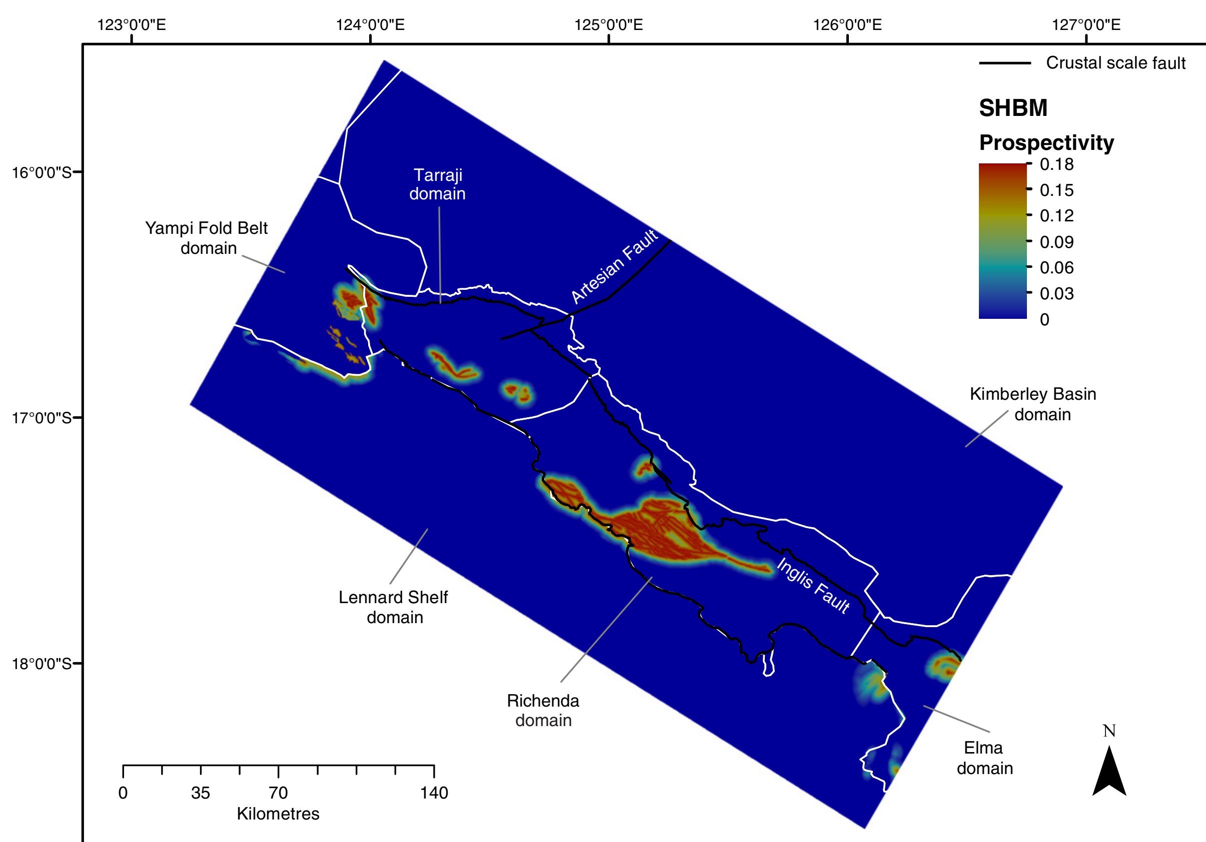

Fig. 10. Fuzzy prospectivity model for the stratiform-hosted base metal mineral system.

as evidence layers. Geophysical forward modelling of gravity and magnetic data has also indicated the presence of basement highs in the Lennard Shelf that extend from the Oscar Range Inlier (Fig. 4e Profile 2 at x = c. 80 km) (Lindsay et al., 2015). Other evidence layers include a transfer fault (oriented north-northeast) and the edges of the Lennard Shelf limestone (as representative of pathways), and the Lennard Shelf limestone as the trap.

The most prospective regions in our model for MVT prospectivity abut the west-northwest, east-southeast trending crustal-scale fault that separates the Lennard Shelf from the King Leopold Orogen (Fig. 11). A prospective region is located on the northern and southern edges of the 67-mile high, which possibly acted as a series of basement highs, focussing mineralised fluids toward carbonate host rocks. This large region may host significant undercover MVT deposits.

3.5. Sn–W mineral systems

A broad prospectivity model based on commonly accepted components has been adopted to accommodate a dearth of Sn–W exploration data in this region. The Paperbark Supersuite granites have been selected as the source rocks, deep-penetrating structures (**0.63**) and other faults that permit fluid migration represent potential pathways, and altered rocks or those with high chemical reactivity are the traps.

Two areas of relatively high prospectivity are revealed from Sn–W prospectivity modelling (Fig. 12). The first lies in the south of the Tarriji domain and is associated with Paperbark Supersuite rocks with higher alteration, high chemical contrast across geological contacts between the Ruins Dolerite and the Paperbark Supersuite granites and a series of faults and shears. The second high prospectivity area is in the northwestern part of the Elma domain, which is proximal to the Paperbark Supersuite. High chemical contrast between the Hart Dolerite and the Speewah Group, relatively high alteration and a series of faults are present in this location.

3.6. Intrusion-related base metals and Au prospectivity

Mafic rocks (Hart Dolerite, Ruins Dolerite) and granites (Paperbark Supersuite) are considered the main potential metal source. Deep penetrating faults (**0.63**) are considered to be important as fluid pathways as they may also define craton or lithospheric boundaries. Other faults are included as potential fluid pathways (Fig. 13). The Wotjulum Porphyry, structurally complex regions or altered rocks are likely traps for IRBM, porphyry-style mineral systems.

The Yampi Fold Belt domain and the northern part of the Richenda domain host the highest prospectivity for porphyry-style mineralization of the IRBM mineral system (Fig. 13). In the Yampi Fold Belt domain, the coincidence of the Wotjulum Porphyry with faults leads to high prospectivity values, suggesting possible porphyry-hosted mineral systems. The northern central part of the Richenda domain is a structurally complex region which also exhibits relatively high alteration. The proximity of both the Hart Dolerite and Paperbark Supersuite contribute to the high prospectivity of this region.

4. Discussion

Geological interpretations of the upper crustal part of each forward model profile reveal that the Inglis Fault and with lesser confidence, the boundary between the Lennard Shelf and Paperbark Supersuite are deep penetrating structures, and thus important inputs to prospectivity modelling as potential fluid conduits (Fig. 4). In addition, the boundary between the Fitzroy Trough and Lennard Shelf appears to be a fundamental crustal boundary. While just outside the study area, the Pinnacle Fault System is still important for the CHBM mineral system

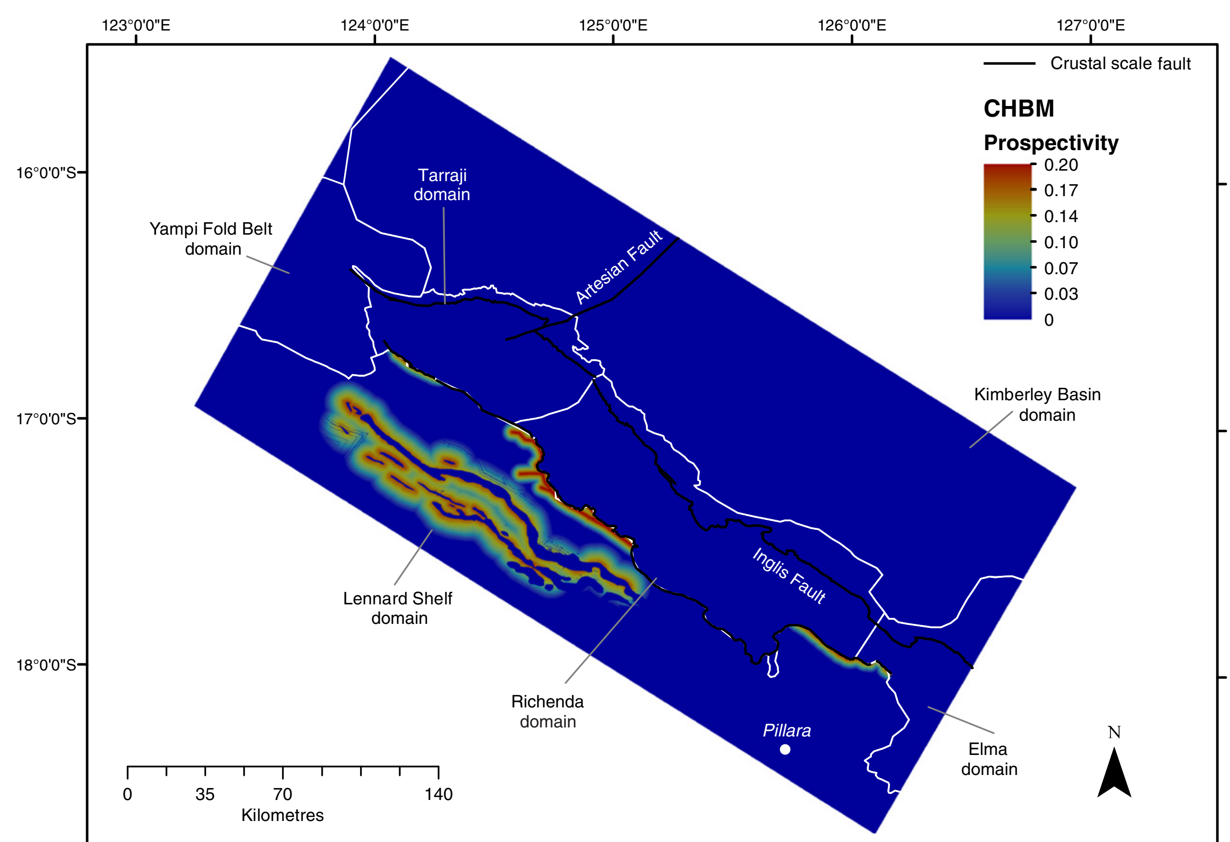

Fig. 11. Fuzzy prospectivity model for the carbonate-hosted base metals mineral system. The white dot indicates the location of the Pillara MVT district.

model as a likely conduit for mineralizing fluids. The magnetic bodies interpreted to form the 67-mile high represent fairly discrete steeply dipping bodies with moderate density. These may represent magnetic facies of the Oscar Range Group and form a basement high, and display higher prospectivity values for the carbonate-hosted base metals.

The presence of a deep-penetrating structure like the Artesian Fault between Profiles 1 and 2 (Fig. 4a) can explain these along strike differences, and could have focussed pluton emplacement away from the north face of the Inglis Fault north of the Tarraji domain. The deep and penetrating nature of the Artesian Fault is supported by structural interpretation and previous work by Gunn and Meixner (1998). The presence of such basement-seated structures has implications for the tectonostratigraphic evolution and mineral prospectivity of the Kimberley Basin. These structures may have provided a conduit for mantle fluids and are important components of the mineral systems framework. The structures may also have provided a conduit for eruption and controlled the location of source vents for the Hart-Carson large igneous province. The hypothesis of Gunn and Meixner (1998) that these crustal-scale structures only affect the Kimberley Basin rocks is modified in this study, as the Artesian Fault described above is extended into the King Leopold Orogen. Other boundaries like those suggested by Gunn and Meixner (1998) may also indicate other crustal-scale, deep penetrating structure that affect and control basement and overlying rocks of the Kimberley Basin and King Leopold Orogen. Further modelling and analysis with potential field (e.g., forward modelling sections trending west-northwest and parallel to the Orogen), magnetotelluric (Spratt et al., 2014) or seismic data (Hocking et al., 2015) would allow a more definitive assessment of the presence of craton-scale controls within the study area.

Support for the Inglis Fault as a deep, penetrating structure is provided by the structural interpretation, forward modelling and field observations. The entire northern edge of the King Leopold Orogen is interpreted to be bounded by the Inglis Fault, the fault plane of which exhibits a deformed geometry, in contrast to interpreted linear faults linked to late events in the Kimberley Basin. The importance of fluid pathways in magmatic and hydrothermal mineral systems is a central component to the mineral systems approach to mineral prospectivity mapping and their successful identification is critical. The influence of deep-penetrating crustal-scale features is evident in the magmatic-related hydrothermal mineral system results. A high map weight was assigned to these structures to reflect their importance in the relevant conceptual mineral system models, though the pathway class weight reduces their influence in the final prospectivity models. Nonetheless, most regions of high prospectivity in the west Kimberley are associated with the presence of deep penetrating, crustal-scale features. In nature discrete features such as faults focus mineralization processes (Hronsky and Groves, 2008), and the same is true for faults represented in digital evidence layers in that they constrain prospectivity to discrete locations. One may suggest that high prospectivity values are simply the result of higher weightings assigned to deep-penetrating structures, however the necessary geological units, whether acting as a source or trap, must also be spatially linked. Further, prospectivity models were calculated using the product of values (i.e., Fuzzy PRODUCT), which serves to decrease the calculated prospectivity value. Thus low membership values have the greatest influence on final prospectivity values. Most low values are seen in the trap class, appropriately reflecting the level of knowledge in an underexplored region.

As expected, some drawbacks were identified. The most obvious was that the MVT Pillara District is not identified in this analysis (Fig. 11 — white dot). The absence of this anticipated result does not invalidate the model, but suggests that the essential components of the Pillara MVT system have not been reliably mapped by the selected predictor maps. In particular, transfer faults were indistinct in the potential

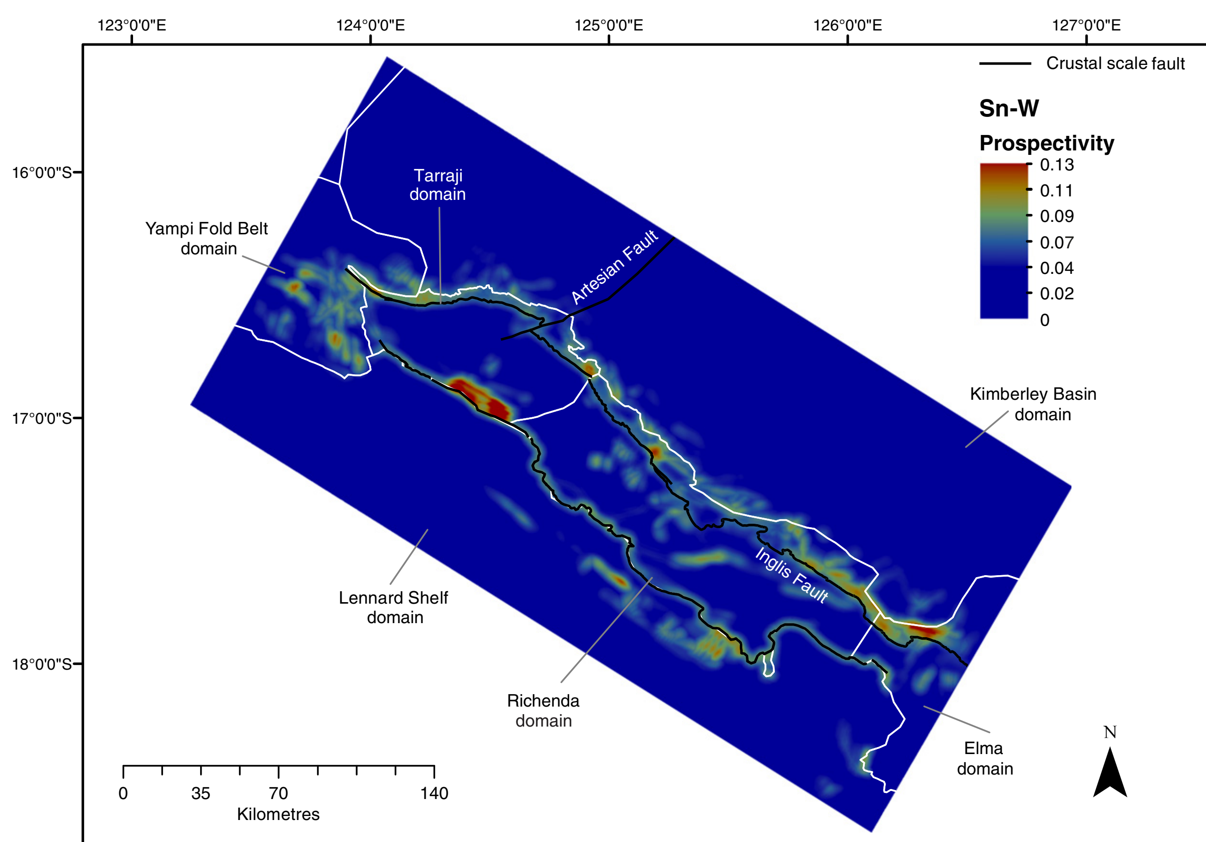

Fig. 12. Fuzzy prospectivity model for the intrusion-related base metal (Sn–W) mineral system.

field data, and more detailed analysis would better constrain their presence and location. Other apparently smaller-scale faults may be included in the CHBM mineral system as splays to larger-scale transfer faults.

The issue of scale becomes apparent in the failure of the CHBM model to predict known deposits. Selection of the boundaries to the study area and the detail at which to perform the geophysical interpretation appear to be influential in the result. The boundaries to the study area are close to the Pillara district and may have contributed to this failure, a phenomenon that would not be limited to just this example. Important proxies for locating a deposit (or district) may be just outside the boundaries of the study area. This is relevant to the CHBM model, as the source of fluids are thought to be from the southwest, in the Canning Basin (D'Ercole et al., 2000; Dörling et al., 1996). One solution may to be expand the boundaries of the study area in order to provide a solution to the problems above. The consequence is either more time would be needed to examine the expanded region, or result in a corresponding decrease in interpretation detail.

Finally, the boundaries of the study area were selected without much consideration for the Pillara district (as its location was already known) as the focus was on calculating mineral prospectivity in regions closer to the centre of the study area. While the prospective regions provided by this model are conceptually valid; identification and measured inclusion of evidence that highlights the Pillara district could improve the predictive power of future analyses. Finding the perfect balance between project completion time, scale and interpretation resolution is difficult: preference to one detracts from the others. The result is that some parts of the model end up misrepresenting the intended aim of the study.

4.1. Addressing subjectivity in knowledge-driven modelling

The flexibility of knowledge-driven prospectivity methods allows a range of commodities in underexplored regions to be analysed. Such analysis requires a degree of subjective decisions to be made about which evidence layers are included for analysis, and how each layer is processed (distance thresholds, uncertainty factors, various weightings etc.). Objectivity can be retained by taking the approach described in this analysis by creating a suite of evidence layers that apply to all mineral systems. As evidence layers represent some geological phenomena related to mineralization, each layer should exhibit the same properties, regardless of the mineral system it is associated with. For example, the influence of the deep-penetrating crustal-scale Inglis Fault as a magmatic fluid conduit on the Ni-sulphide, Orogenic Au, Sn–W, and IRBM mineral systems should be the same. Any differences in location of prospectivity should be left to the evidence layers representing the source or trap. There is a high risk of overfitting analyses if ‘fine-tuning’ the attributes of distance buffers, weightings or inclusion of individual evidence layers occurred and would result in biased and potentially inaccurate results. Further, using the same suite of evidence layers allows performance comparison of prospectivity modelling in multi-commodity analyses to be performed.

By treating each distance-based evidence layer with a linear decrease, or using the same density function for structural layers an easier comparison can be made. If different distance techniques (such as a sigmoidal or logarithmic decrease) or density methods were used, these would introduce more degrees of freedom to the analysis, making comparison more complicated. Differing performance of prospectivity models could be due to either the data or the evidence layer preparation method. Thus analyses, such as the reduction of search space examination performed here, would be subject to more uncertainty. By using a consistent method and input across all types of evidence layers, this form of stochastic uncertainty is avoided.

Nonetheless, more meaningful results could be produced if the focus of this study was on individual mineral systems, rather than the multi-commodity approach taken here. Using a sigmoidal decrease in fuzzy

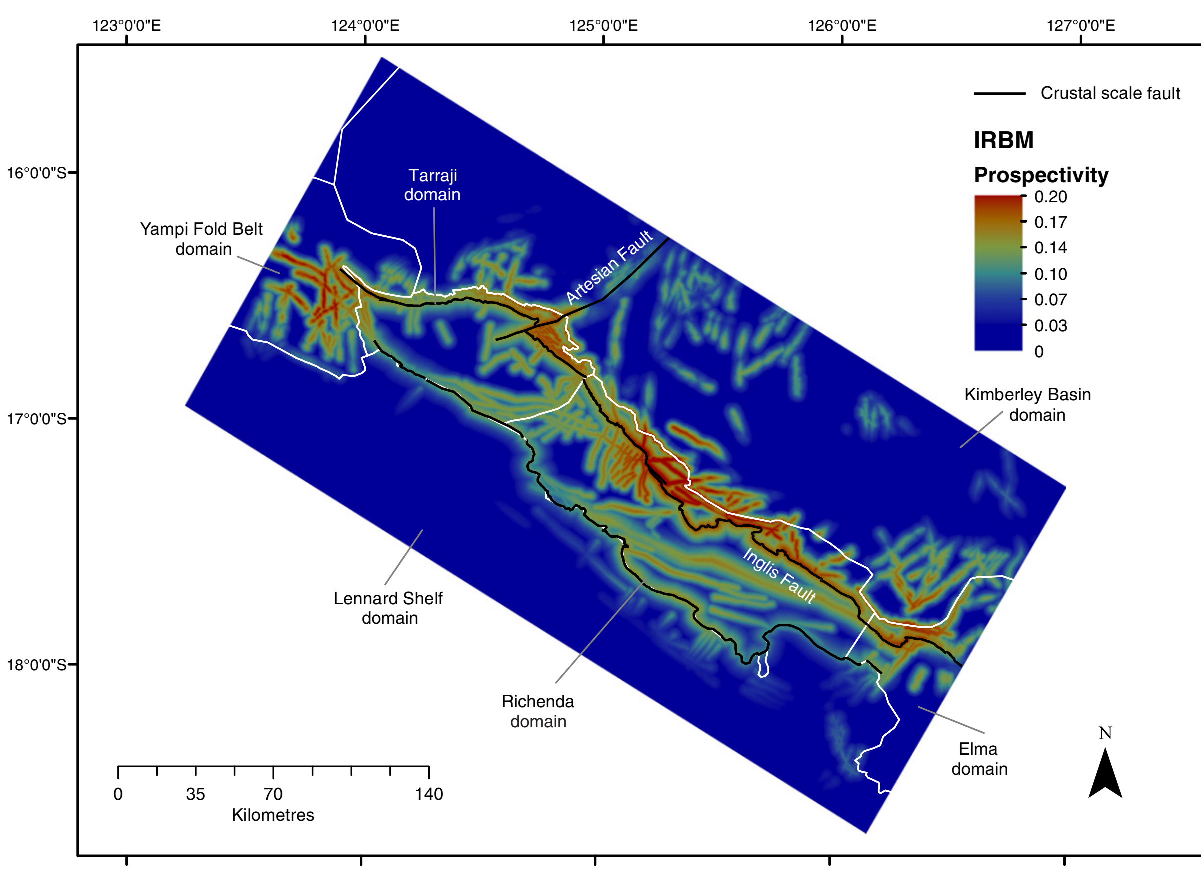

Fig. 13. Fuzzy prospectivity model for the intrusion-related base metal (porphyry Cu–Au).

Table 5
Search area reduction statistics, showing how prospectivity analyses can greatly reduce the area of further detailed analysis required for target detection at deposit to camp scales. Percentages of the total region of interest are shown with corresponding area in km^2.

Mineral System	Percentage of map in the 50th percentile of prospectivity values (unprospective)	Area (km^2)	Percentage of map in top 10th percentile of prospectivity values (highly prospective)	Area (km^2)
Carbonate-hosted base metals	96.2214	62,781.60	0.1537	100.28
Intrusion-related base metals	88.6916	57,868.63	0.1524	99.46
Ni-sulphide	96.4839	62,952.88	0.1208	78.80
Orogenic Au	89.5320	58,416.95	0.4779	311.82
Sn–W	99.6582	65,023.98	0.0044	2.85
Stratiform-hosted base metals	96.9439	63,253.01	1.2400	809.07
			Total study area = 65,247 km^2	

values from faults (Carranza, 2010) instead of a linear decrease may have been useful for the Ni-sulphide mineral system, where prospectivity is likely at depth where prospective mafic units and faults intersect. In some cases, such as the IRBM and CHBM mineral systems, use of a fractal dimension map to represent pathways and traps may have proven effective. Au deposit distribution in the Boulder–Lefroy shear zone (Western Australia) region exhibit predictable relationships when examined using fractal dimensions (Weinberg et al., 2004). Indeed, the tyranny of scale, which is linked with the failure of the CHBM model to predict existing deposits, can be mitigated through mapping complexity using fractal dimensions (Ford and McCuaig, 2010). Both these techniques require justification through the use of extensive deposit databases, rendering them inappropriate in the west Kimberley. They could have been used in select circumstances to produce better results, but would have made overall analysis inconsistent across the different commodities and resulted in overfitting.

4.2. Reducing the geographical search space

Table 5 shows the reduction in search space achieved by the prospectivity analyses. If the top tenth percentile of prospectivity values are considered to be the most attractive for explorers, then all analyses reduced the search space to less than one percent of the of the total study area. The one exception is the SHBM analysis, which reduced the search space slightly less, to less than two percent of the total study area. The top tenth percentile of prospectivity value represent areas between 809.07 km^2 (SHBM) and 2.85 km^2 (Sn–W), from an initial study area of 65,247 km^2. If the fiftieth percentile of prospectivity values is considered to be unprospective, the analyses show that 88% of the study area can be ignored. The lower fiftieth percentile of prospectivity values represent areas between 57,868.63 km^2 (IRBM) and 65,023.98 km^2 (Sn–W).

Approximately one percent of the total study area was shown to be highly prospective, or in the ninetieth percentile of prospectivity values (Table 5). In geographic terms, this reduces the area of ground to be analysed at camp to deposit scales to 100.28 km^2 (CHBM), 99.46 km^2 (IRBM), 78.80 km^2 (Ni-sulphide), 311.82 km^2 (Orogenic Au), 2.85 km^2 (Sn–W) and 809.07 km^2 (SHBM). Explorers may want to look beyond the highest prospectivity values, and would be justified in doing so given the assumptions and approximations required in prospectivity modelling. If the lowest 50% of prospectivity values were considered unappealing for further analysis (and the highest 50% are included) the search space is still greatly reduced, with greater than 88% (IRBM) to 99% (Sn–W) of the study area highlighted as unlikely to yield success, and can subsequently be ignored in further detailed analysis. The techniques described in these analyses exhibit the effectiveness of prospectivity techniques in reducing the search space for explorers, making project generation workflows in greenfields regions more efficient. As shown in this analysis, a very small percentage of the original study area need be further analysed, allowing more time to be devoted to the difficult task of target detection at deposit to camp scales.

5. Conclusion

This study sought to develop a broader understanding of the King Leopold Orogen and the adjacent Kimberley Basin and Lennard Shelf with a view to better characterisation of mineral exploration potential. We identified, through potential field interpretation, the undercover extents of the main lithological units, and clarif the extents of major suites, such as the Ni-prospective Hart Dolerite. Furthermore, we linked our interpretations to the structural history of the region including the events of the Hooper, Yampi and King Leopold orogenies. Inputs from analyses of crustal-scale tectonic architecture were supplied by geophysical interpretation and 2.5D magnetic and gravity modelling. Several major crustal-scale faults have been associated with regions of high prospectivity including the Artesian Fault and Inglis Fault. In particular, the Inglis Fault shows clear association with the larger Hart Dolerite sills, indicating an influence on the magmatic system, and potential mineralization.

Mineral prospectivity models have exploited these new geological insights resulting in the first comprehensive multi-commodity mineral systems analysis for the west Kimberley. Although these represent a simplistic and subjective view of the mineral systems, they highlight some key features. Orthomagmatic Ni sulphide prospectivity is, conceptually, best developed where the Hart Dolerite is coincident with intersecting crustal-scale faults. We image this clearly for one locality in the Tarraji Domain, however this relationship may also apply to other localities within the Kimberley Basin and Halls Creek Orogen where we did not image deep penetrating faults. The most prospective regions for carbonate hosted base metals are the margins of the Lennard Shelf, but only in the western half of the Lamboo Province. Volcano-sedimentary hosted base metal prospectivity is restricted to the Marboo Formation, with other potential targets returning very low prospectivity. Orogenic Au shows strong relationships with fault networks, especially along the Inglis Fault, and less so along the Sandy Creek Shear Zone. Intrusion related base-metal prospectivity is not dissimilar to the orogenic Au, in that they are both strongly influenced by crustal structure. There is however a stronger focus around the Inglis Fault, especially in the central region. Sn–W prospectivity is generally low, with one “warm-spot” in the southwest Lamboo Province.

Subjectivity inherent in knowledge-driven prospectivity analyses has been mitigated by the use of a suite of evidence layers that were not modified according to mineral system. The use of a suite of evidence layers also permitted the comparison of prospectivity results. The reduction of search space exhibited by the techniques described in this analysis highlight how improved workflow efficiency can be gained through knowledge-driven mineral systems analysis in greenfields regions.

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