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EXPLORATION INCENTIVE SCHEME

Centre for EXPLORATION TARGETING

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Cover photograph: Hart Dolerite sills, east Kimberley

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Accompanying GIS data including ARC Toolbar, explanatory notes and videos are available as a zipped file on <www.dmp.wa.gov.au/ebookshop>.

Prospectivity analysis of the Halls Creek Orogen, northern Western Australia — using a Mineral Systems Approach

by

SA Occhipinti[1], V Metelka[1], MD Lindsay[1], JA Hollis[2], AR Aitken[1], S Sheppard[3], K Orth[4], IM Tyler, T Beardsmore, M Hutchinson and JM Miller[1]

Abstract

Opening up greenfields regions of Western Australia for mineral exploration programs is best facilitated through the understanding of regional mineral prospectivity. A multi-commodity mineral systems analysis has been carried out as the basis for prospectivity analyses and mapping in the greenfields Halls Creek Orogen in northern Western Australia. Known mineral occurrences or deposits in the region formed from c. 1860 Ma to 350 Ma, largely influenced by periods of supercontinent assembly and breakup, manifested in the region through the contractional 1865–1850 Ma Hooper and 1835–1805 Ma Halls Creek Orogenies and the 1000–800 Ma Yampi, c. 560 Ma King Leopold, and 450–295 Ma Alice Springs Orogenies interspersed with periods of relaxation accompanied by extension and basin formation. Prospectivity models were generated for seven commodity groups of various ages and ore genesis mechanisms within the region that include combinations of Ni, Cu, PGE, V, Ti, Au, Pb, Zn, and diamonds. A link was found between key mineral systems and prospectivity model components and the distribution of disparate styles of mineral deposits in the region. Crustal-scale tectonic architecture was analysed by combining a 2D map view geological–geophysical interpretation with 2.5D magnetic and gravity joint inversions of selected profiles, a 3D Moho gravity inversion (MoGGIE), and inferences derived from a 2D magnetotellurics experiment conducted in the northern part of the region. Different 'zones' (tectonic terranes) of the Halls Creek Orogen are prospective for diverse commodity groups due to the tectonic environment in which they developed through time, their potential to be preserved at the present day surface or subsurface, and favourable depositional sites that may be present in these zones (structural or lithological). Major crustal-scale faults or shear zones that intrinsically control the location of known ore deposits in the area are implied to be sites of fluid migration and proximal to sites of ore deposition. Of these, orogen-perpendicular (northwesterly trending) and orogen-oblique (northerly trending) faults seem to be the most influential structures with respect to ore deposition in the Halls Creek Orogen, especially in regions where they intersect each other or orogen-parallel (northeasterly trending) major crustal-scale structures.

KEYWORDS: crustal-scale structures, Halls Creek Orogen, Kimberley region, mineralisation, mineral systems, orogeny rifting, subduction, tectonics, Tickalara Arc

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Introduction

The aim of this study was to complete a multicommodity mineral systems analysis of the Halls Creek Orogen and is not meant to be a detailed documentation of ore deposits and ore occurrences in the region, which have previously been undertaken by Sanders (1999) and Hassan (2004). The mineral systems analysis was completed using a staged approach:

- analysing the 4D tectonic framework of the region
- determining what the most likely periods of mineralization of certain commodity groups might be
- delineating units that are considered to be fertile for a certain commodity group or be proxies for fertility
- constructing a combined structural map from geophysical and geological datasets that informs ideas regarding fluid pathways and depositional trap sites for mineralization
- producing a geological–geophysical map as a GIS project, derived from Geological Survey of Western Australia (GSWA) datasets and all of the above analyses to inform a semi-automated prospectivity analysis.

The geological map used for much of the analysis contains several attributed features for each identified unit, including: GSWA rock code, group name, formation name, rock types, metamorphic grade (limited to the Hooper and Halls Creek Orogenies), and expected mineralization type. The structural map used was attributed for major or minor structures and — where understood — structure types (e.g. strike-slip fault or thrust; Lindsay et al., 2016). These datasets are available in the GIS project that accompanies this report as a zipped file.

The aforementioned attributed features were used to apply a semi-automated approach to mineral systems analysis and prospectivity analysis (targeting) at the regional to district scale in the Halls Creek Orogen. In recent years there has been much emphasis placed on collating proxies to source, pathways, and traps for the purpose of mineral systems analysis. This has led to the popularity of GIS-based predictor maps as a method for delineating these proxies for disparate types of mineral systems. Such an approach has been variously discussed by Begg et al. (2009, 2010), McCuaig et al. (2010), and McCuaig and Hronsky (2014). However, for this analysis we used a slightly different, more generic approach that is appropriate for a multicommodity, large-scale mineral systems analysis, using the features of:

- deep crustal-scale architecture
- fertility, geodynamic throttle, and depositional site
- preservation.

This approach recognizes the complexity of ore deposit system models. However, it groups their most pertinent features and allows unusual or disparate mineralization styles to be captured in a semi-automated prospectivity analysis.

In this report we briefly review different mineral systems that are currently recognized in the Halls Creek Orogen and define the common and most important features that can be used for mineral systems analysis. This review draws heavily on compilations of different mineral deposits by various authors (Hart et al., 2004; Gurney et al., 2005; Leach et al., 2005, 2010; Groves and Bierlein, 2007; McCuaig et al., 2010; Cawood and Hawkesworth, 2013).

Mineral systems analysis

Mineral systems analysis involves understanding the geodynamic processes that are required to form and preserve ore deposits at a range of scales (Wyborn et al., 1994). To carry out mineral systems analysis, the key controlling processes on the formation and preservation of mineral systems must be understood. These processes include aspects as large scale as the secular evolution of the Earth, factors controlling lithospheric enrichment, and geodynamic drivers (McCuaig et al., 2010; Cawood and Hawkesworth, 2013; McCuaig and Hronsky, 2014). Of these processes, lithospheric enrichment and geodynamic drivers can often be directly linked to plate tectonics and the kinematics of plate motion, which in turn can be fundamentally linked to the formation and breakup of supercontinents (Goldfarb et al., 2001; Cawood and Hawkesworth, 2013). Mineralization processes related to the secular evolution of the Earth cause some styles of ore deposits to form only during certain periods of the Earth's history (Cline et al., 2005; Leach et al., 2010). Other controlling processes, such as the requirement of specific lithologies as mineralization traps (e.g. carbonate–evaporate sequences) may require the understanding of plate reconstructions to ascertain at what paleolatitudes they can be targeted for certain styles of ores (Cline et al., 2005; Leach et al., 2010).

In this contribution, we first address the tectonic evolution of the Halls Creek Orogen because it is intrinsically linked to the mineral system development in the region. We also consider the formation of major structures through time that may influence the pathways of mineralizing fluids to sites of ore deposition. These structures are interpreted from the upper to lower crust through analysis of geological and geophysical data (Lindsay et al., 2016). Other factors that we consider are the crustal depth that is currently exposed in the surface or present in the shallow subsurface rock types (as hosts or as chemical scrubbers/reactive rocks for their influence on fertility or ore deposition) and structural trap sites (depositional sites).

Tectonothermal evolution of the Halls Creek Orogen

The following discussion is a summary based on the tectonic syntheses of the Halls Creek Orogen proposed in various publications by Hollis et al. (2014), Tyler and Griffin (1990), Sheppard et al. (1999, 2001), and Tyler et al. (1999, 2012).

The geological evolution of the Kimberley region spans more than 2 billion years and involves periods of convergence, accretion, and rifting along a margin that was affected by changing tectonic environments through this time (Tyler and Griffin, 1990; Sheppard et al., 1999; Griffin et al., 2000; Tyler et al., 2012; Hollis et al., 2014) (Figs 1, 2). These changes have led to the development of a region in which rock types that formed in different tectonic settings exist in the same area. Contact relationships between units are varied: they may be tectonically interleaved, conformable, or unconformable over each other or are intrusive, together metamorphosed to different grades and tectonically juxtaposed, or interleaved (Fig. 3).

The unexposed Kimberley Craton, upon which the region is built, is inferred to comprise a series of northeast-trending Archean and Paleoproterozoic terranes (Hollis et al., 2014) and is characterized by fast S-wave velocities down to about 250 km, which is consistent with a thick, cold Archean lithospheric root (Fishwick et al., 2005). These characteristics extend south of the Kimberley Basin – Lamboo Province region, suggesting that the craton extends beneath the Lamboo Province that wraps the southwestern and eastern Kimberley margins (Fig. 1).

The 1910–1805 Ma Lamboo Province is exposed in northeasterly and northwesterly trending orogenic belts that bound the margins of the younger sedimentary rocks of the Speewah and Kimberley groups. The Lamboo Province, in the Halls Creek Orogen in the east Kimberley has been divided into three tectonostratigraphic terranes – the Western, Central, and Eastern Zones (Fig. 2; Tyler et al., 1995). The Central and Eastern Zones are only exposed in the eastern part of the Lamboo Province, whereas the Western Zone is also exposed around the western and central part of the province and forms the basement in the King Leopold Orogen. These Zones contain distinct geological units formed during the early Paleoproterozoic, which may have originated in different tectonic settings or at different times, suggesting that they were juxtaposed from as late as the 1870–1850 Ma Hooper Orogeny to the 1835–1805 Ma Halls Creek Orogeny (Tyler and Griffin, 1992; Griffin et al., 1993, 2000; Page and Hoatson, 2000; Page et al., 2001). Rocks now exposed in the Central and Western Zones were variably metamorphosed from greenschist to granulite facies during the Hooper Orogeny, whereas rocks in the Eastern Zone were not metamorphosed or deformed at this time (Tyler et al., 2012). Unlike the Hooper Orogeny, the Halls Creek Orogeny variably affected all of the eastern Lamboo Province, suggesting that at this time the different tectonostratigraphic terranes (Western, Central and Eastern Zones) of the eastern Lamboo Province were sutured (Tyler et al., 2012; Fig. 3).

A >1900 Ma subduction zone?

The earliest evidence for convergence in the region is postulated to have taken place early in its Paleoproterozoic history (Griffin et al., 2000). Griffin et al. (2000) suggested that northwesterly directed subduction along the Kimberley Craton margin took place at >1900 Ma on the basis that the geochemical characteristics of the 1865–1850 Ma felsic to mafic intrusive components of the Paperbark Supersuite suggest that they formed in a post-collisional setting (Fig. 4). Spratt et al. (2014) suggested that a fossil subduction zone, matching the description of that outlined in Griffin et al. (2000), has been imaged in recently published magnetotellurics (MT) data acquired across the east Kimberley region — through the Halls Creek Orogen and over the Kimberley Craton (Fig. 5). However, this feature is intriguing in that the apparent fossil subducted slab is non-conductive in nature; whereas usually subducted slabs are found to be conductive due to their hydrous nature and the zones above them (Spratt et al., 2014). An alternative interpretation would be that the northwest dipping non-conductive material described by Spratt et al. (2014) is a zone of highly resistive Proterozoic granitic rocks emplaced into the lower to upper crust within the Kimberley Craton margin.

Pre- and syn-1870–1850 Ma Hooper Orogeny

Turbiditic rocks of the Marboo Formation, exposed in the Western Zone, may have formed as a result of rifting of the Kimberley Craton margin after this earlier Paleoproterozoic collisional event (Tyler et al., 1999). The rifting and sedimentation took place at c. 1870 Ma, based on the youngest detrital zircon population within the Marboo Formation and the crystallization age of the Paperbark Supersuite that intrudes them (Sanders, 1999; Tyler et al., 1999; Griffin et al., 2000; Hollis et al., 2014). The Marboo Formation was deformed and metamorphosed at low to high grade during the 1870–1850 Ma Hooper Orogeny prior to being overlain by felsic volcanic and volcaniclastic rocks of the Whitewater Volcanics and intruded by granites and gabbros of the cogenetic Paperbark Supersuite. In regions where the Marboo Formation was metamorphosed at medium to high grade during the Hooper Orogeny the metasedimentary rocks have been assigned to separate units — the Amhurst Metamorphics and Mount Joseph Migmatite (Sheppard et al., 1997; Tyler et al., 1999; Tyler, 2015, written comm.). The Whitewater Volcanics may have formed as a result of extensional processes towards the end of the Hooper Orogeny.

The Central Zone of the Lamboo Province initially developed as an oceanic island arc — the Tickalara Arc — that formed at c. 1865 Ma (Fig. 6) over an easterly dipping subduction zone, outboard of the Kimberley Craton (Sheppard et al., 2001). Sedimentary rocks and mafic volcanic and volcaniclastic rocks of the Tickalara Metamorphics were deposited at this time, and then intruded by tonalite, trondhjemite, and quartz diorite sheets of the juvenile Dougalls Suite (Sheppard et al., 2001; Kemp et al., 2015). The Dougalls Suite locally has Sr/Y >40, for SiO_2 >60 weight % (see Sheppard et al., 2001), which is indicative of felsic igneous suites prospective for Cu-fertile porphyries in Phanerozoic terranes (Loucks, 2014). Supracrustal rocks of the Tickalara Metamorphics, and the Dougalls Suite were deformed and metamorphosed at high temperature, low pressure amphibolite to granulite facies at 1865–1856 Ma and 1850–1845 Ma, during and after the 1870–1850 Ma Hooper Orogeny (Bodorkos et al., 1999; Blake et al., 2000; Page et al., 2001; Bodorkos and Reddy, 2004).

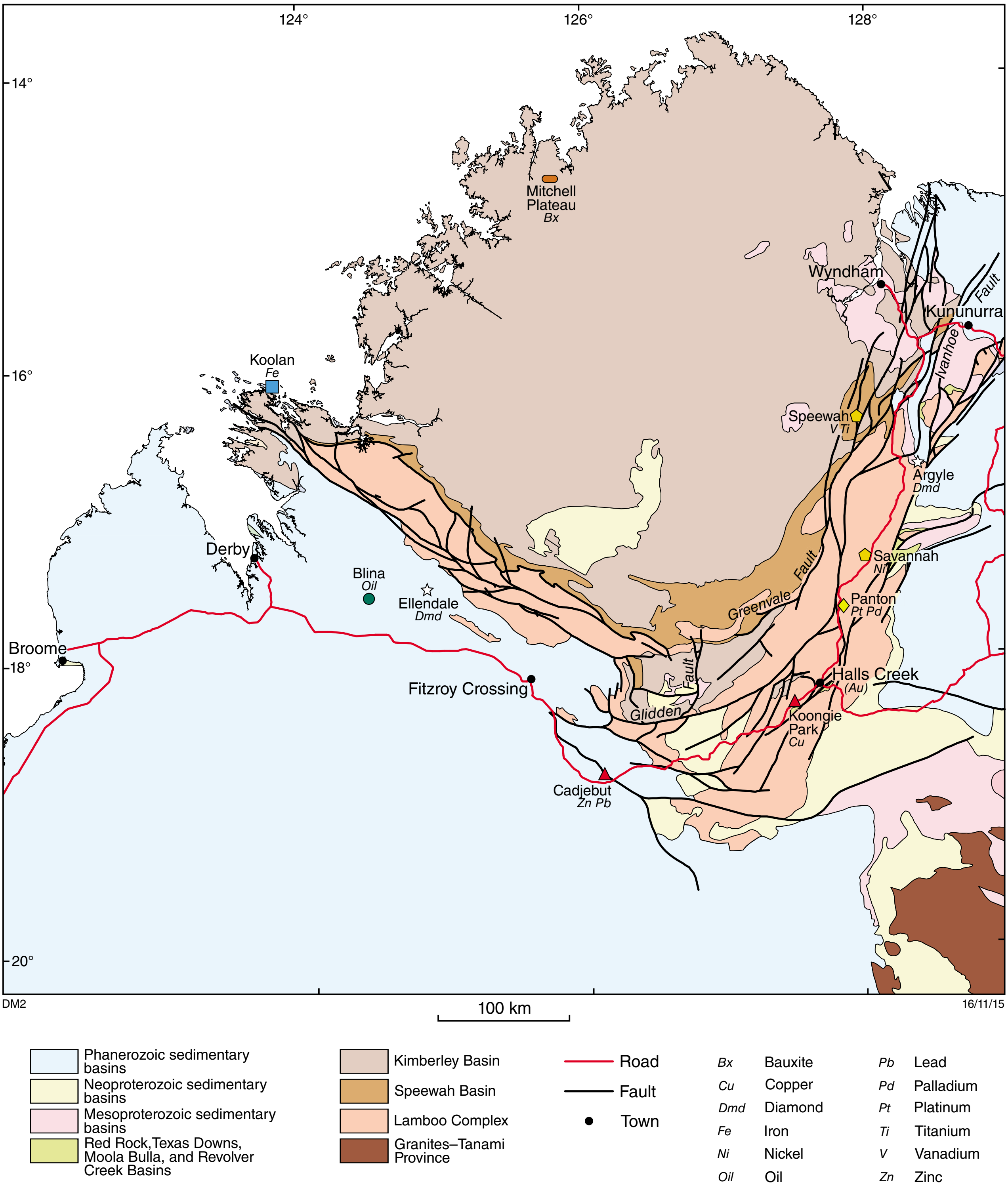


Figure 1. **Tectonic units in the Kimberley region (adapted from Tyler et al., 2012; Hollis et al., 2014)**

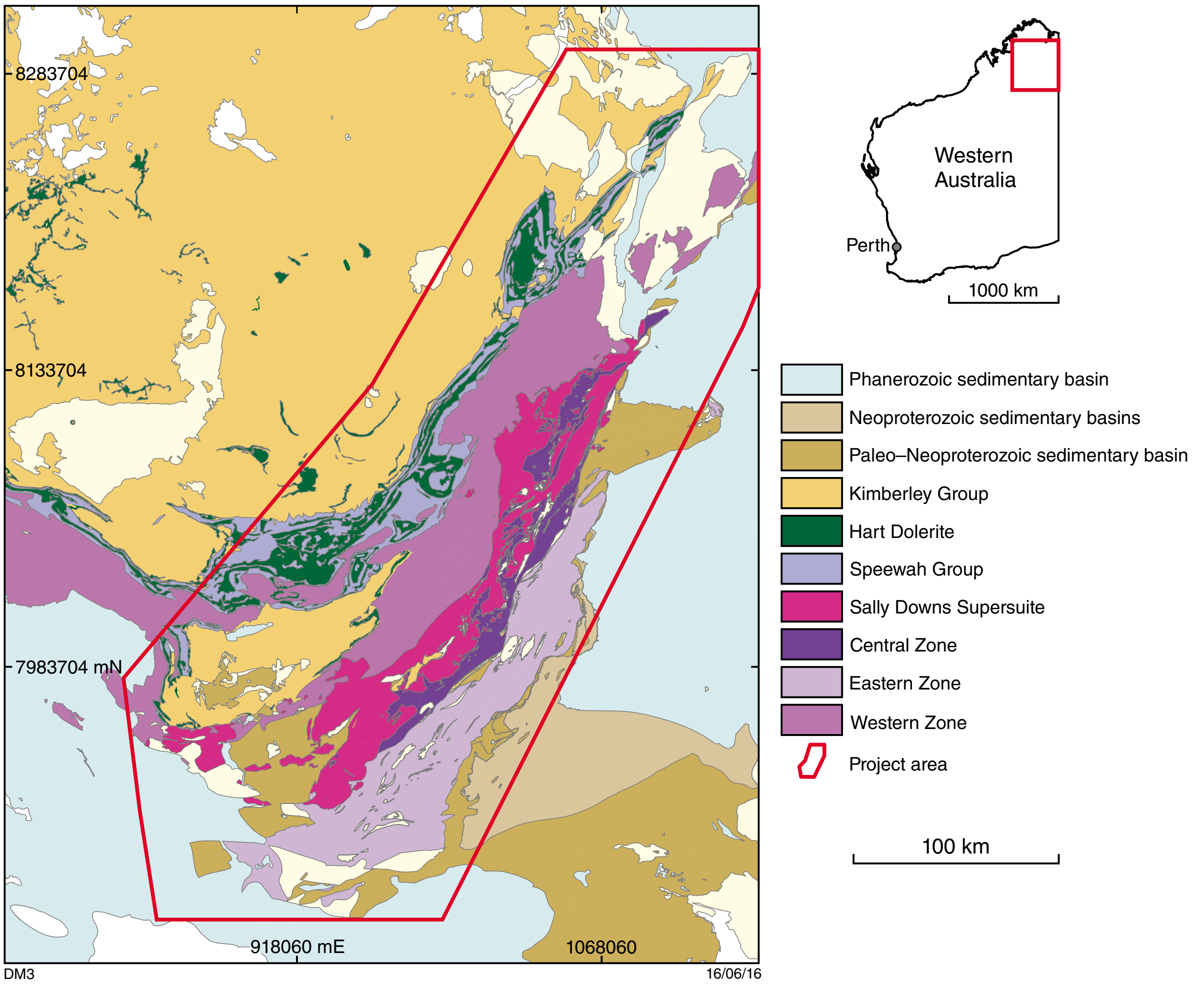


Figure 2. Map of Eastern, Central, and Western Zones of the Lamboo Province within the Halls Creek Orogen

The Hooper Orogeny only affected rocks in the Western and Central Zones of the Lamboo Province. At this time the rocks within these Zones were variously metamorphosed from greenschist to granulite facies and were tectonically juxtaposed by 1850 Ma.

Paleoproterozoic passive to active margin formation — 1910 to 1850 Ma — Eastern Zone

The Eastern Zone of the Lamboo Province contains felsic and mafic volcanic rocks and sedimentary rocks that developed over a passive continental margin on the western margin of the North Australian Craton (Fig. 6; Tyler et al., 2012). The oldest known rocks in the Eastern Zone are the felsic and mafic volcanic rocks and associated granites of the c. 1910 Ma Ding Dong Downs Volcanics. These were unconformably overlain by siliciclastic sedimentary and volcanic rocks of the Halls Creek Group between 1880 Ma and 1847 Ma. The basal Halls Creek Group consists of the largely siliciclastic Saunders Creek Formation that is overlain by c. 1880 Ma mafic volcanics of the Biscay Formation. The Biscay Formation is overlain by turbiditic rocks of the Olympio Formation, recording a transition from a passive to active margin by c. 1850 Ma (Blake et al., 1999, 2000; Tyler et al., 2012). Intrusion of the Woodward Dolerite into the Halls Creek Group after c. 1850 Ma may indicate a period of relaxation and local extension.

Relaxation and plate reorganization post-Hooper, pre-Halls Creek Orogenies

Emplacement of the first layered mafic–ultramafic intrusive rocks into the Western and Central Zones of the Lamboo Province in the Halls Creek Orogen took place between 1859 Ma and 1853 Ma. In the Western Zone it may be partly contemporaneous with the intrusion of the Paperbark Supersuite (Hoatson and Blake, 2000; Tyler et al., 2012). The possible contemporaneous intrusive relationship is indicated by the presence of net-vein complexes, back-veining, and complex mingling relationships of the gabbro with the Paperbark Supersuite (Blake et al., 2000).

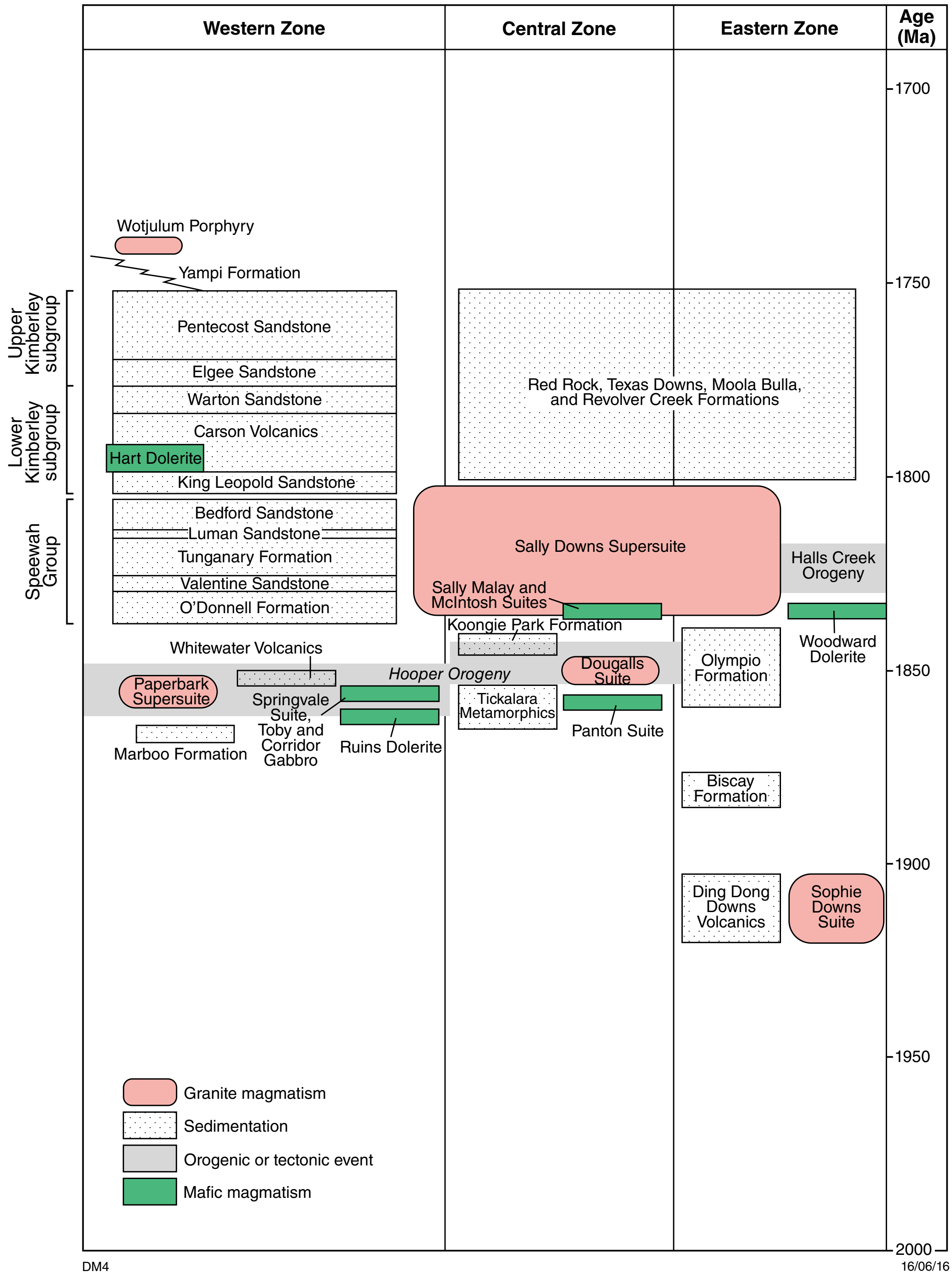


Figure 3. **Time–space plot illustrating the relative development of the Eastern, Central and Western Zones of the Halls Creek Orogen – eastern Lamboo Province (from Hollis et al., 2014)**

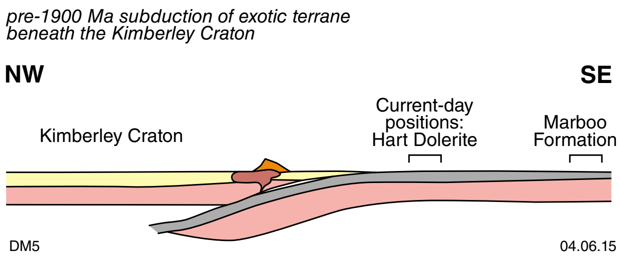


Figure 4. **Subduction of an unknown 'exotic' continental fragment pre-1900 Ma beneath the Kimberley Craton. Grey unit includes oceanic crust. Modified after Griffin et al. (2000).**

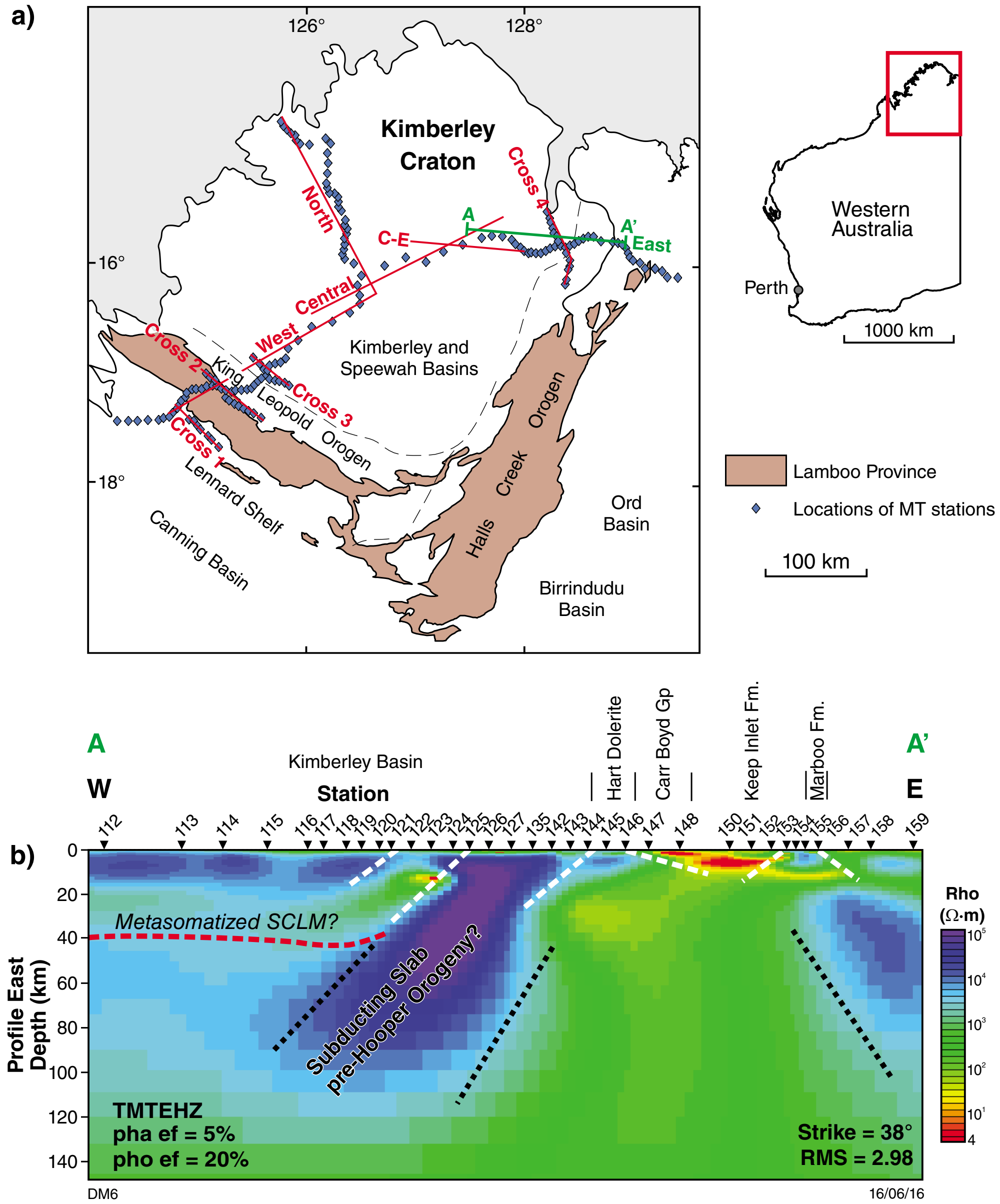


Figure 5. Magnetotellurics image generated from data from the Halls Creek Orogen – Kimberley Craton line from Spratt et al. (2014). The northwest dipping resistor has been proposed as evidence of a pre-1900 Ma slab that Griffin et al. (2000) postulated must be have been subducted beneath the Kimberley Craton, prior to the Hooper Orogeny.

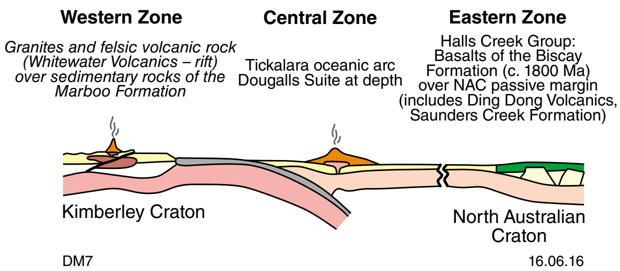


Figure 6. Convergence of the Kimberley Craton and North Australian Craton (NAC) during the 1870–1850 Ma Hooper Orogeny [modified after Griffin et al (2000) and Tyler et al (2012)]. Zigzags illustrate either an unknown distance along the North Australian Craton segment or an unknown relationship between the two areas separated by the zigzag subdivision.

Within the Western Zone, layered mafic–ultramafic intrusions of the c. 1857 Ma Springvale Suite and c. 1855 Ma Toby Gabbro intrusions were emplaced at depths of 8–18 km into the Paperbark Supersuite and Marboo Formation (Hoatson and Blake, 2000; Hoatson, 2000; Fig. 7). At the same time in the Central Zone, the c. 1856 Ma mafic–ultramafic Panton Suite intrusions were emplaced into the Tickalara Metamorphics (Fig. 7).

The present-day exposure of units metamorphosed and deformed during the Hooper Orogeny illustrates the relative exhumation of different fault blocks, which contain rocks metamorphosed at different pressures and temperatures (see Fig. 12a). These variable degrees of exhumation in the northeasterly trending belt took place either in the late Hooper Orogeny, during rifting after the Hooper Orogeny and before the Halls Creek Orogeny or during the Halls Creek Orogeny (see below discussion). Alternatively, relative exhumation of different regions in the Eastern and Central Zones took place during all of the above periods — from c. 1850 Ma to c. 1805 Ma — leading to the variable current day exposure of rocks originally metamorphosed in the mid to upper crust.

The cessation of the Hooper Orogeny resulted in rifting of the Tickalara Arc during a period of plate reorganization between 1845 Ma and 1840 Ma (Tyler et al., 2012) or just prior to the Halls Creek Orogeny (Fig. 8), resulting in extrusion of felsic and mafic volcanics and deposition of sedimentary rocks of the Koongie Park Formation and the intrusion of the layered mafic to ultramafic Sally Malay Suite (Sewell, 1999; Tyler et al., 2012). The Koongie Park Formation is restricted to the central to southern part of the Central Zone of the Lamboo Province. The Sally Malay Suite that developed contemporaneously but at deeper crustal levels, on the other hand, is restricted to the northern part of the Central Zone, suggesting that exhumation in the north was greater than in the south after their emplacement.

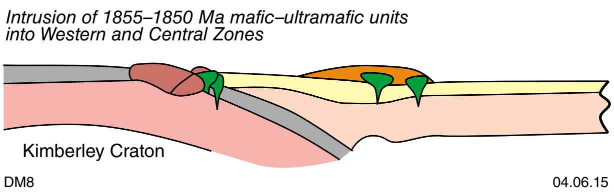


Figure 7. Intrusion of 1855–1850 Ma mafic and ultramafic rocks of the Springvale Suite, Toby Gabbro, Panton Suite, and Corridor Gabbro

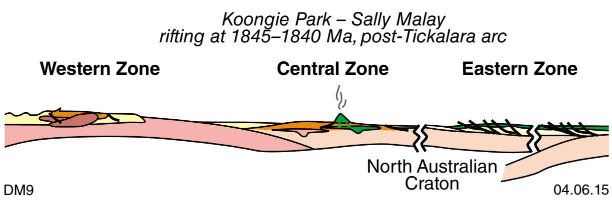


Figure 8. Development of Koongie Park Formation (green) and Sally Malay Suite (subsurface) in an extensional setting over the previously formed Tickalara arc (orange) in the Central Zone of the eastern Lamboo Complex. Development of the Eastern Zone at this time is not well understood. Its eastern part may have developed in an active margin setting at c. 1850 Ma to a west-dipping subduction zone (current-day coordinates). Zigzags illustrate either an unknown distance along the North Australian Craton segment or an unknown relationship between the two areas separated by the zigzag subdivision.

1835–1805 Ma Halls Creek Orogeny

The 1835–1805 Ma Halls Creek Orogeny affected the Western, Central, and Eastern Zones of the Lamboo Province and is thus considered to reflect suturing of the Kimberley Craton and North Australian Craton (Sheppard et al., 1999, 2001; Tyler et al., 2012). At this time, voluminous felsic to mafic granites and mafic rocks of the Sally Downs Supersuite intruded into the region and the mafic igneous McIntosh Suite intrusions were emplaced in the central part of the Central Zone.

Granitic intrusions of the Sally Downs Supersuite have been broadly subdivided into the Mabel Downs, Syenite Camp, and Kevins Dams suites, which all have slightly different chemistries consistent with different petrogenesis (Sheppard et al., 2001). Although Sally Downs Supersuite igneous rocks intrude across the western to eastern parts of the Lamboo Province, they are most common in the Central Zone. The chemistry of the Sally Downs Supersuite suggests that all of its components were formed in a subduction zone setting or from melting of rocks formed in relation to a subduction zone. Isotopic data suggest that they contain a proportion of mantle-derived material in their magmatic source region (Sheppard et al., 2001) (Fig. 9).

The Mabel Downs Suite, which consists largely of hornblende and hornblende–biotite tonalite and quartz diorite is exposed in the Central Zone and considered to be the oldest component of the Sally Downs Supersuite. Its chemistry overlaps both Archean high-Al tonalite–trondhjemite–granodiorite TTG suites and Phanerozoic adakites (Sheppard et al., 2001). Sheppard et al. (2001) suggest that the Mabel Downs Suite formed over a west or northwest dipping subduction zone early in the Halls Creek Orogeny and was later metamorphosed and deformed at amphibolite facies conditions.

Other components of the Sally Downs Supersuite include the Kevins Dam and Syenite Camp suites. Like the Mabel Downs Suite, these rocks are inferred to have formed above a westerly or northwesterly dipping subduction zone during the Halls Creek Orogeny (Tyler et al., 2012). The Syenite Camp Suite contains biotite–(hornblende)-bearing granodiorite, tonalite, and monzogranite that was emplaced synchronously with gabbro and hybrid rocks into the Central Zone of the Lamboo Province (Sheppard et al., 2001). Granites of the Syenite Camp Suite reportedly represent crustally derived melts — perhaps melting of quartz diorite to tonalitic compositions — and are transitional between the Mabel Downs and Kevins Dam suites.

The McIntosh Suite mafic intrusions are in the Central Zone of the Halls Creek Orogen and intrude the Tickalara Metamorphics. The McIntosh Suite intrusions consists of olivine gabbro and gabbronorite, troctolite, magnetite gabbro, leucogabbro, and peridotite and are considered to be c. 1830 Ma, based on the age of hornfelsed, migmatized metasedimentary rocks of the Tickalara Metamorphics that it intrudes (Page and Hoatson, 2000). This age is broadly concurrent with the early stages of the high-temperature, low-pressure Halls Creek Orogeny (Bodorkos and Reddy, 2004) of which the metamorphic grade of currently exposed rock is highest in the central part of the Central Zone (Fig. 12).

West of the Halls Creek Orogen, the Speewah Group siliciclastic sedimentary rocks and minor felsic volcanics were deposited over the Kimberley Craton towards the end of the Halls Creek Orogeny. Unconformably overlying the Speewah Group is the Kimberley Group, which was intruded by mafic rocks of the c. 1797 Ma Hart Dolerite. The Hart Dolerite, together with the associated mafic Carson Volcanics, is considered to be part of a large igneous province (LIP) (Sheppard et al., 2012). After this time, sedimentary rocks were deposited across the region in a series of discrete depositional basins (Tyler et al., 2012).

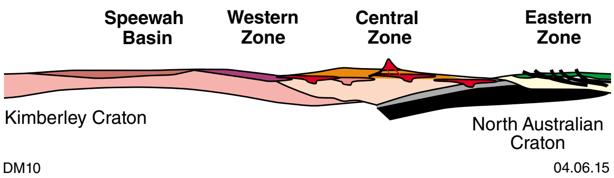


Figure 9. Schematic diagram illustrating the formation of the Sally Downs Supersuite (red unit), synchronous to suturing of the Eastern, Central, and Western Zones during the 1835–1805 Ma Halls Creek Orogeny

Mineral prospectivity of the Halls Creek Orogen

The Halls Creek Orogen hosts a variety of mineralization styles, with only some being mined. These have been previously documented in GSWA reports by Sanders (1999), Ferguson (1999), and Hassan (2004); thus, detailed descriptions of these deposits will not be listed in this Report. At the time of writing, operating mines in the Halls Creek Orogen included: Ridges Iron Ore (iron), Savannah and Copernicus (nickel, copper, cobalt), and Argyle (diamonds). However, the east Kimberley has many different styles of mineral deposits or occurrences documented, including rare earth elements (REE), Au, Pb, Cu, Zn, Ag, Sn, Ta, and W in the Halls Creek Group (Eastern Zone) and Au, Cu, Pb, Zn, Ni, Co, platinum group elements (PGE), and graphite in the Central and Western Zones.

For this contribution, we apply a mineral systems approach to targeting for a variety of ore types (Tables 1 and 2). The key to such an approach is to understand the basic elements that are required to form, focus, deposit, and preserve a mineral deposit. For these components of the analysis, we have taken into account:

- Lithospheric/crustal architecture or deep crustal-scale structures that may have formed during the early history of the Halls Creek Orogen, but have likely been reactivated during subsequent events
- Regional-scale metamorphic breaks that could indicate the presence of deep penetrating crustal-scale structures
- The geodynamics or tectonic triggers throughout the development of the region
- The fertility of elements preserved in the area which can be influenced by secular earth evolution, the paleolatitude of the region through time, and the preserved lithostratigraphy
- The depositional site of commodities or groups of commodities, which may often coincide with certain tectonostratigraphic units or zones of structural complexity
- Consideration of current-day level of crustal exposure (i.e. upper, middle, or lower crust) as a proxy for factors that may influence the preservation of different styles of mineralization.

By using a mineral systems approach, the prospectivity of the region for disparate commodities can be considered. In this contribution, we assess the prospectivity of the region for diamonds, PGE, NiS, Cu, Au, Zn, Pb, REE, rare metals, and Au.

Crustal-scale architecture (deep crustal-scale structures)

Deep crustal-scale structures or whole-of-lithosphere structures are understood to control lithospheric architecture and therefore influence the development and emplacement of a wide range of mineral deposits (McCuaig et al., 2010; Snyder, 2013; McCuaig and Hronsky, 2014). Thus, their identification is fundamental for any study (White and Muir, 1989; Bierlein et al., 2006; White et al., 2014). In some regions, disparate mineral deposits that formed in diverse tectonic settings and at vastly different times are present along the same structure (O'Driscoll, 1981; McCuaig et al., 2010; McCuaig and Hronsky, 2014). Deep crustal-scale or whole-of-lithosphere structures are known to form in active continental and oceanic arc regions subparallel and orthogonal to the advancing subduction zone (Garwin, 2005; Sillitoe, 2008; White, 2014), with the orthogonal structures represented by transform faults. In these regions, porphyry and epithermal deposits appear to develop over deep-seated structures, particularly where they intersect each other as is demonstrated in regions such as Southeast Asia and the West Pacific (Garwin et al., 2005; White et al., 2014).

Table 1. Mineral systems summary for intraplate–basin formation (in extension and compression), extension, and rifting. CD = clastic dominated Pb–Zn deposits; SEDEX = sedimentary exhalative deposits.

Unit	*Deep crustal-scale structure*	*Geodynamic throttle*	*Fertility*	*Deposition*	*Preservation*	*Commodities*	*Ore deposit model*
Marboo Formation and Amhurst Metamorphics	In central to southern part of the Western Zone northerly, northwesterly, and northeasterly trending faults/ shear zones from gravity and magnetics	Rifting/ deposition	Deposited above presumed Archean basement	Can current areas of exposure be correlated with deposition sites — basin development? If so, then possible zones adjacent to major crustal structures more prospective?	Upper to middle crust	Pb, Zn	Clastic-dominated Pb deposit (Zn discounted, because possibly no mafic input at this time?)
		Halls Creek Orogeny	Upper plate of west-dipping subduction zone — possibly forms basement to back-arc	Kinks in northeasterly trending faults interpreted from magnetics intersection zones between: 1. northwesterly trending (orogen-normal) and northeasterly trending (orogen-parallel faults) 2. north trending major faults and northeasterly trending orogen parallel faults		Au	Orogenic Au
Paperbark Supersuite	Northerly, northwesterly, and northeasterly trending faults/ shear zones from gravity and magnetics	Hooper Orogeny or end/ after Hooper transtension or extension	Over paleosubduction zone — fertile zone or maybe connectivity to lower crust or upper mantle — mafic–ultramafic rocks But on lower plate during Hooper Orogeny	Kinks in northeasterly trending faults interpreted from magnetics. Intersection zones between: 3. northwesterly trending (orogen-normal) and northeasterly trending (orogen-parallel faults) 4. north-trending major faults and northeasterly trending orogen parallel faults 5. over/in mafic to ultramafic rocks 6. felsic volcanics and upper parts of intrusives.	Greenschist to amphibolite facies Upper to middle crust	Ni, Cu, Sn, W, Zn, Pb, Nb, Mo	Orthomagmatic NiS and Cu Sn/W in granites. Epithermal rift (felsic volcanics)
		Halls Creek Orogeny — compression or transpression (sinistral)	Over paleosubduction zone — fertile zone On upper plate to down- going slab (North Australian Craton slab)	As for points 1 and 2 above	As above	Au, Cu (remobilized from mafic components of Paperbark Supersuite)	Orogenic Au Remobilized Cu (leaching out of mafic rocks)
Panton Suite	Northeast- and northwest-trending faults	End of Hooper orogeny — transtension or extension	Mafic/ultramafic rocks — connectivity to mantle?	Mafic–ultramafic rocks	High to low grade	Ni	Orthomagmatic NiS

Table 1. continued

Unit	*Deep crustal-scale structure*	*Geodynamic throttle*	*Fertility*	*Deposition*	*Preservation*	*Commodities*	*Ore deposit model*
Sally Malay	On eastern and western margins proximal to mapped deep crustal-scale, orogen-parallel structures	Post Hooper, transtension/ plate reorganization	Mafic–ultramafic rocks Rounded mapped outcrops probably sill-like geometries	Kinks in northeasterly trending faults interpreted from magnetics, i.e. deviation from northeasterly to north-northeasterly trending faults	In area of high metamorphic grade Preservation for Cu, Ni, PGE, and associated minerals at all crustal levels	Ni, Cu, PGE, V, Cr — layered intrusion	Orthomagmatic Ni, Cu, PGE
Koongie Park (includes Onedin Member and Angelo Microgranite)	Northeasterly trending structures bound the unit. In south and on northern boundary, northerly trending structures — are these early extensional faults, bounding a 'basin'?	Post-Hooper, transtension/ plate reorganization	Chemical sedimentary rocks (reactive and rheological) and mafic and felsic components	In chemical sedimentary rocks around areas of intersection of north and northeasterly trending faults		Cu, Au, Ag, Pb, Zn	VMS, Au over VMS in orogenic setting, possible porphyry in extensional setting (not over arc)
Hart Dolerite	Northeasterly and northerly trending structures intersect and over northerly trending Speewah Structure	Post Halls Creek reorganization	Mafic rocks	In mafic rocks		Cu, V, Ti, PGEs (at depth?)	Layered differentiates /orthomagmatic
Halls Creek Group – Biscay Formation	On westernmost boundary of Eastern Zone. Regional northeasterly trending faults and kinks in regional-scale northeasterly trending fault zones. Little Mount Isa Group around kink (northeasterly to northerly to northeasterly trending) 30 km south of northwesterly trending deep crustal-scale structure.	Rifting along passive margin pre-Halls Creek Orogeny, perhaps transition to deepening of basin	Volcanics and chemical sedimentary rocks Metals in solution	Syngenetic — in stratabound successions. Possibly requires carbonates or lower pressures for deposition Structural sites around granite basement highs, adjacent to older basin-forming structures. In neck zones where confining pressure high, fluid movement focused	Upper to middle	Pb, Zn, Cu (if mafic input), Ag, Au	SEDEX, CD deposits

Table 1. continued

Unit	*Deep crustal-scale structure*	*Geodynamic throttle*	*Fertility*	*Deposition*	*Preservation*	*Commodities*	*Ore deposit model*
Halls Creek Group – Olympio	Northeasterly trending on eastern edge of Halls Creek. Group margin northwesterly trending in central part of belt	Unknown	Unsure. Fertility of belt could be initially related to eastwards subduction of ?unknown terrane at c. 1850Ma beneath the proto-Eastern Zone	Some units more fertile than others, e.g. possible felsic volcanics (Maude Healy Member) for Au Depositional sites (structural) set up during Halls Creek Orogeny. However, possible Au mineralization during late stages of the Halls Creek Orogeny during sinistral transpression Complex structural zones that could be the sites of growth faults (more work required to delineate these) Proximal to deep crustal-scale structures	Upper crust	Pb, Zn, Cu (if mafic input), Ag, Au	SEDEX, CD — deposit Pb, Zn
Argyle Lamproite(s)	At junctions of northeasterly and northwesterly trending major crustal structures over Central Zone	The formation of supercontinent Rodinia — local plate reorganization	Alkaline intrusives/volcanics over SCLM fertilized during Hooper and Halls Creek Orogenies. Archean crust at depth; indicators include high K (radiometrics), Ti, Ba, Zr, and Nb. Also nontronite and smectite clays (high Mg)	Junction of northeastern and northwestern faults	Low metamorphic grade for preservation of host rock, but not for diamond preservation	Diamond	Diamond pipes — alkaline intrusives

Table 2. Mineral systems summary for convergence, accretion, and collisional processes in the Halls Creek Orogeny

Unit	*Deep crustal-scale structure*	*Geodynamic throttle*	*Fertility*	*Deposition*	*Preservation*	*Commodities*	*Ore deposit model*
Tickalara Metamorphics	Northerly, northwesterly, and northeasterly trending faults/ shear zones from gravity and magnetics	Halls Creek Orogeny	On upper plate of subduction zone — fertile zone, perhaps connectivity to the lower crust or mantle and therefore zone of mineralization from metalliferous fluids	Chemical contrast between sedimentary rocks, mafic volcanics Kinks in northeasterly trending structural grain of the Halls Creek Orogen; fold hinge zones Resolution of mapping not appropriate to find chemical contrasts between different rock types in the analysis	Amphibolite or above	Au	Orogenic Au Possibly metamorphosed orogenic Au formed during Hooper Orogeny

Table 2. continued

Unit	*Deep crustal-scale structure*	*Geodynamic throttle*	*Fertility*	*Deposition*	*Preservation*	*Commodities*	*Ore deposit model*
Dougalls Suite	Northerly, northwesterly, and northeasterly trending faults/ shear zones from gravity and magnetics	Hooper Orogeny	Upper plate of east-dipping subduction zone — oceanic arc	Within the juvenile felsic igneous rocks, but preferably those preserved in the greenschist facies or below	Amphibolite	Cu, Au, Mo	Felsic to intermediate intrusion related (but inboard from subduction zone) Porphyry-related Cu–Au–Mo mineralization in an arc setting
Mabel Downs Suite (Sally Downs Supersuite)	Northerly, northwesterly, and northeasterly trending faults/ shear zones from gravity and magnetics	Halls Creek Orogeny	Upper plate of west-dipping subduction zone — formed in arc setting	Within the juvenile felsic igneous rocks, but preferably those preserved in the greenschist facies or below	Amphibolite to granulite	Cu, Au, Mo	Felsic to intermediate intrusion related (but inboard from subduction zone) Porphyry-related Cu–Au–Mo mineralization in an arc setting
Koongie Park Formation	Northwesterly and northeasterly trending faults and shears	Halls Creek Orogeny (late, collisional)	On upper plate of subduction zone — fertile zone, perhaps connectivity to the lower crust or mantle and therefore zone of mineralization from metalliferous fluids Remobilization of earlier formed VMS- style mineralization	Chemical contrast between sedimentary rocks, mafic volcanics, and older gneisses. Kinks in northeasterly trending structural grain of the Halls Creek Orogen, fold hinge zones	Greenschist facies	Au	Orogenic Au
Halls Creek Group – Olympio Formation	Northeasterly (and northwesterly) trending faults and shears	Halls Creek Orogeny (late, collisional)	Connectivity to fluids migrating up the slab during subduction, or maybe crust fertilized during earlier event and then fluid migration, concentration of Au took place during Halls Creek Orogeny	Kinks in northeasterly trending regional structural grain Northeasterly trending fold hinge zones Within specific units — trachytic	Prehnite-pumpellyite to greenschist facies	Au	Orogenic Au

Whole-of-lithosphere structures are also present in intracratonic regions. In these regions suture zones, which represent the old margins of continental lithospheric blocks formed following subduction, have remained as fundamental deep lithospheric-scale structures many millions of years after their development (O'Driscoll, 1981; Gorczyk et al., 2013).

Iron oxide–copper–gold (IOCG) deposits in the Gawler Craton in South Australia formed in the region of (but not directly over) the intersection of a subduction zone that developed during the Paleoproterozoic with westerly dipping subduction beneath the Gawler Craton (Groves et al., 2010; Hayward and Skirrow, 2010) and orthogonal deep crustal-scale structures (Hayward and Skirrow, 2010). In this case, the formation of the IOCG deposits may be linked to a zone of metasomatism in the subcontinental lithospheric mantle (SCLM) that was reactivated during the mineralizing event at c. 1590 Ma (Hayward and Skirrow, 2010; Hobbs et al., 2012). Similarly in the Musgrave Province, Ni–Cu–PGE mineralization takes place over the region of a triple junction between the West Australian, North Australian, and South Australian Cratons (Gorczyk et al., 2013; Smithies et al., 2011). In this region, the mantle lithosphere is thought to have been metasomatized and is overlain by a strongly sheared crust (Gorczyk et al., 2013).

Deep crustal-scale structures in the Halls Creek Orogen have been recognized mainly through analysis of gravity, magnetic, remote sensing, and geological data (Lindsay et al., 2016). Breaks in gravity data and abrupt changes in orientation of magnetic foliations in magnetic images are taken to represent faults and shear zones. In some instances, there is a mismatch between faults and shear zones interpreted from gravity and magnetic data, which might suggest a dip component on the structures that can be mapped from these datasets. In general terms, breaks in gravity data are taken to represent deeper crustal-scale structures than those often observed in magnetic data. This is because magnetic data may only reflect changes in the upper to middle crust (down to about 10 km), although this is not always the case (Lindsay et al., 2016).

The three zones that make up the Halls Creek Orogen — the Western, Central and Eastern Zones — are separated by large-scale orogen-parallel faults or shear zones. Although reactivated throughout the Paleoproterozoic, these boundaries are considered to have formed through accretion and collisional processes (Sheppard et al., 1999, 2001; Tyler et al., 2012) — the Central and Western Zones juxtaposed during the Hooper Orogeny and the combined Western and Central zones juxtaposed against the Eastern Zone during the Halls Creek Orogeny (Sheppard et al., 1999; Blake et al., 2000; Tyler et al., 2012).

A structural map derived from the interpretation of potential field datasets (see Lindsay et al., 2016) in 2D, 2.5D and 3D illustrates this relationship and the influence of orogen-parallel structures in the region (Fig. 11; Lindsay et al., 2016). Orogen-parallel faults and shears often form major boundaries between lithological units within the Western, Central and Eastern Zones. It suggests that they influenced the emplacement of mafic and felsic intrusive rocks and basin formation and the subsequent deposition of sedimentary, volcanosedimentary, and volcanic extrusive rocks into the Halls Creek Orogen after their formation.

Interpreted orogen-normal and a few northerly trending faults or shear zones in the Halls Creek region cut through orogen-parallel faults and shears in the Halls Creek Orogen. In the surface and subsurface, orogen-normal structures appear steep and locally form bounding structures to different lithological units within the Western, Central and Eastern Zones. They also notably separate units that have been metamorphosed at different temperatures and pressures, illustrating that they have facilitated vertical displacement (Lindsay et al., 2016). This is especially obvious in the central part of the Halls Creek Orogen, where outcrop of the Tickalara Metamorphics metamorphosed to granulite facies to form a northeasterly trending lozenge that is truncated in the north and south by northwesterly trending deep-seated faults (Fig. 12; Lindsay et al., 2016). The age of orogen-normal faults and north-trending, deep crustal-scale structures in the region is problematic. It is apparent that orogen-normal faults cut through the Eastern Zone. Thus they were probably active during the Halls Creek Orogeny. However, analysis of a Hooper Orogeny metamorphic grade map in the region also suggests that these structures may have been in operation during the Hooper Orogeny, as they are coincident with rock packages metamorphosed at different metamorphic grades and juxtaposed through faulting and shearing (Fig. 12; see also additional data in zipped data files).

A c. 460 km-long, northerly trending, and probably steeply dipping deep crustal-scale shear zone mapped from gravity and magnetic data cuts across the Western, Central and Eastern Zones of the Halls Creek Orogen (Fig. 11). The age of this structure is unknown, but it displays sinistral strike slip movement. The structure is present in regional-scale MT and forward models for the region (Spratt et al., 2014; Lindsay et al., 2016). However, in the regions around or 'above' this northerly trending shear zone, the trend of geological units is oblique to the regional structural trend (usually northeasterly — Halls Creek Orogen-parallel) and in some extreme cases their trend is subparallel to the shear zone (i.e. northerly trending; Lindsay et al., 2016), illustrating that this structure has partly controlled the deposition and subsequent deformation of geological units forming within or over it. For example, sills of the Hart Dolerite, which intruded along the entire margin of the Kimberley and Speewah Basins, generally form orogen-parallel sheets. In the northeast, on the other hand, a synclinal keel of Hart Dolerite has a northerly strike above and adjacent to the northerly trending deep-crustal scale structure mapped by Lindsay et al., (2016). This suggests the structure is older than the Hart Dolerite and controls the emplacement of the Hart Dolerite in this region. In fact, the northerly trending, deep crustal-scale structure may have formed as early as the Hooper Orogeny or at least by c. 1850 Ma because mafic to ultramafic components of this age (Corridor gabbro) seem to be spatially associated with it.

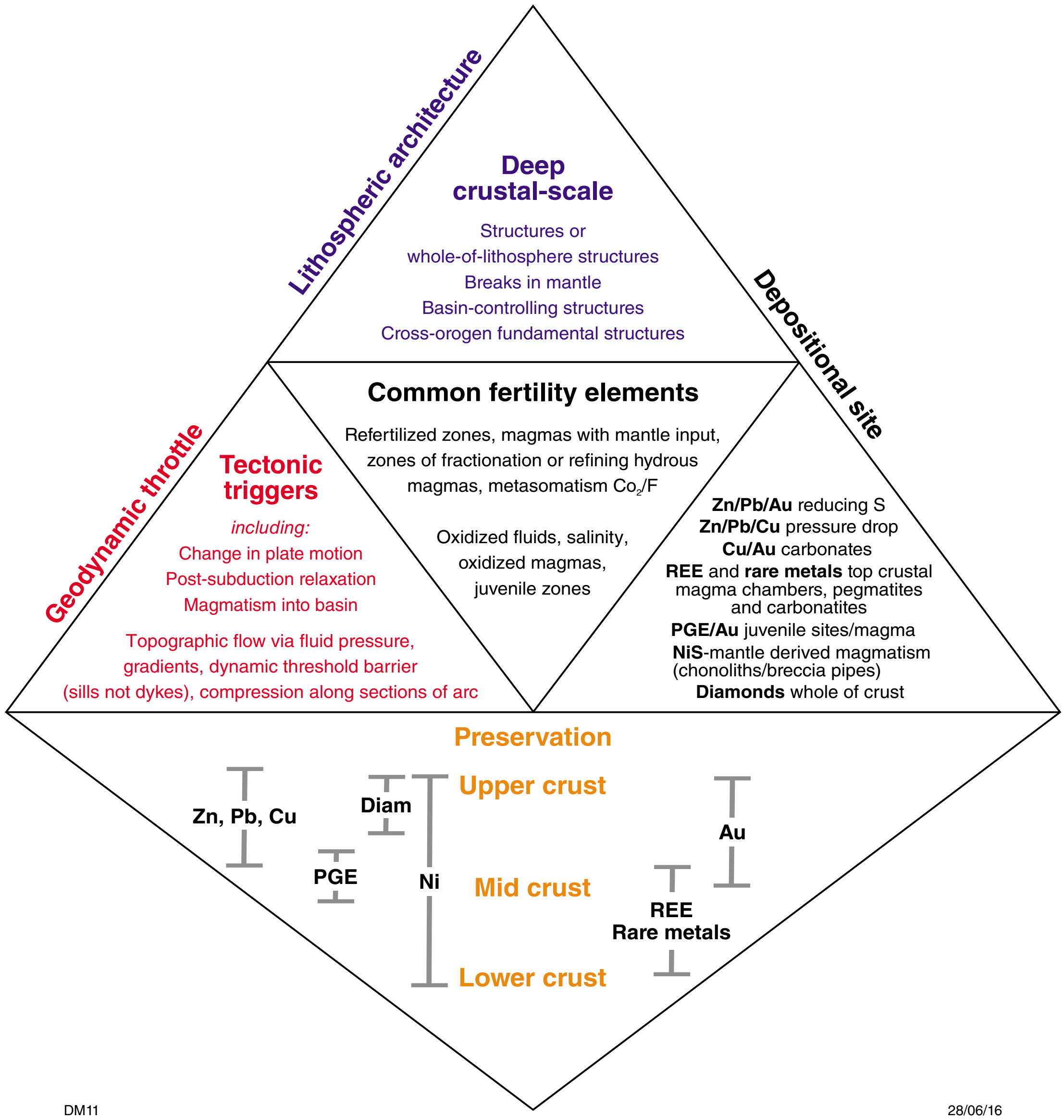


Figure 10. Mineral systems diamond; schematic diagram illustrates the main components required to form and preserve the listed mineral deposits

Analysis of mineral occurrences illustrates their close association with major faults and shear zones mapped in the region throughout the Halls Creek Orogen. Gold appears to be the most common metal associated with orogen-parallel structures, although there are clusters of gold occurrences around the areas in which orogen-parallel and orgogen-perpendicular structures intersect — especially in the Eastern Zone (see additional data in zipped data files). Intrusion-related Sn mineralization lies on or close to northerly, northeasterly, or northwesterly trending structures. Orthomagmatic Ni–Cu, with or without PGE mineralization, appears in association with mafic and ultramafic rocks in the region. However, these occurrences are closely associated with deep crustal-scale faults mapped from the gravity and magnetic data. In addition, the world-class Argyle diamond mine is situated at the confluence of an orogen-normal fault and a northerly trending, deep-seated structure.

Metamorphic discontinuities

Attributes of metamorphic grade were compiled for this project for rocks metamorphosed during the Hooper and Halls Creek Orogenies and can be viewed in the additional data in zipped data files accompanying this Report. A summary is discussed in Lindsay et al. (2016) and presented in Figure 12. In this map, the relative pressure and temperature of regional-scale metamorphism has been summarized through careful analysis of GSWA data points, published studies (Bodorkos et al., 1999; Tyler et al., 1999, 2012; Bodorkos and Reddy, 2004), and GSWA petrological analysis (WAROX database; GSWA, 2015). Mapped changes in the distribution of metamorphic grade from the Hooper and Halls Creek Orogenies are interpreted as representing fault displacements. Rocks that were metamorphosed under high temperatures and relatively low pressures crop out in a northeasterly

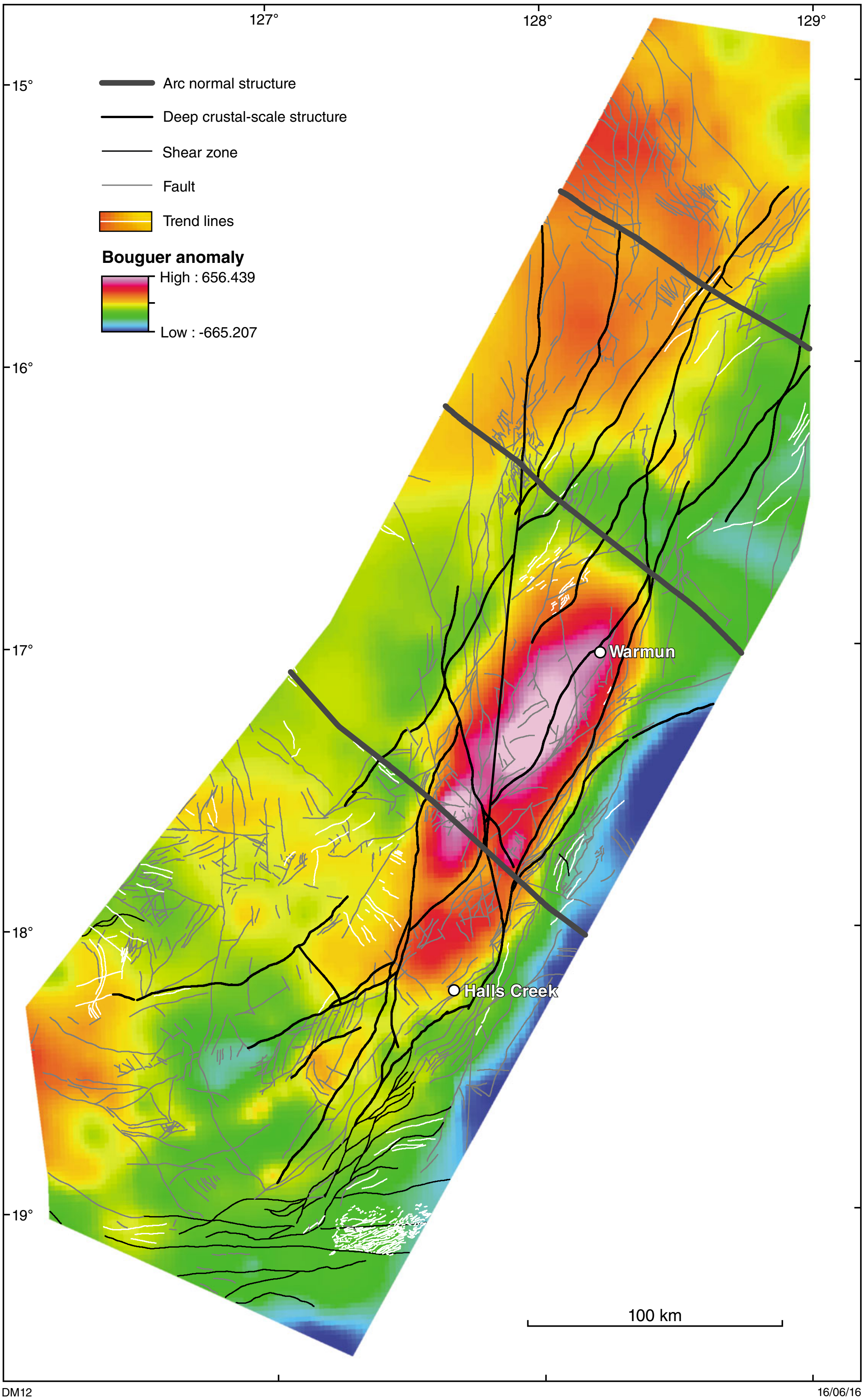
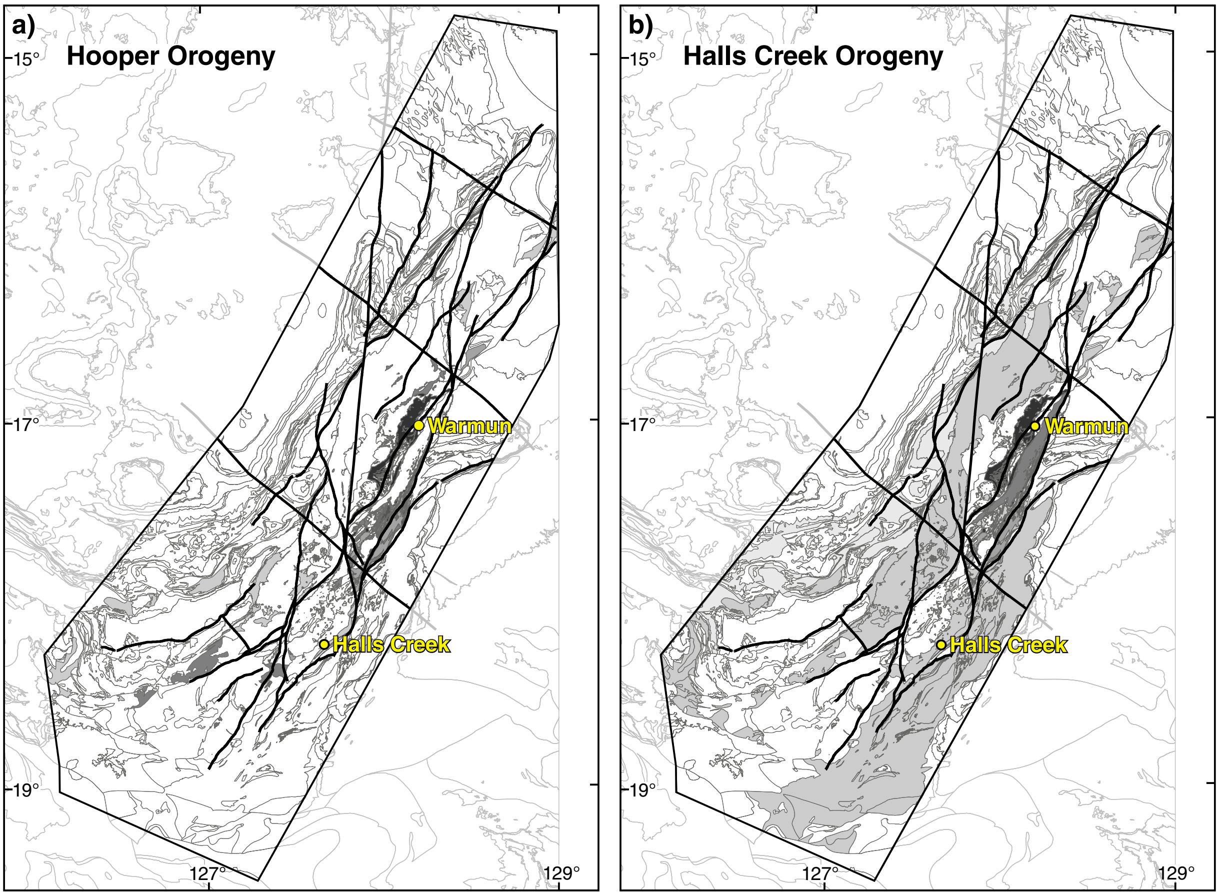
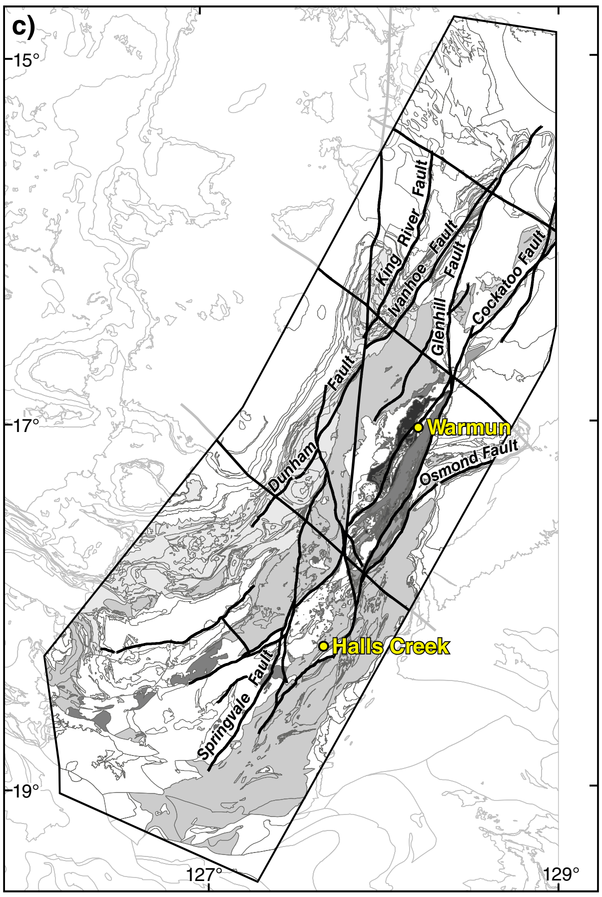


Figure 11. Structural elements of the Halls Creek Orogen delineated from geophysical data and the geological and metamorphic maps, overlain on a Bouguer gravity image (from Lindsay et al., 2015)





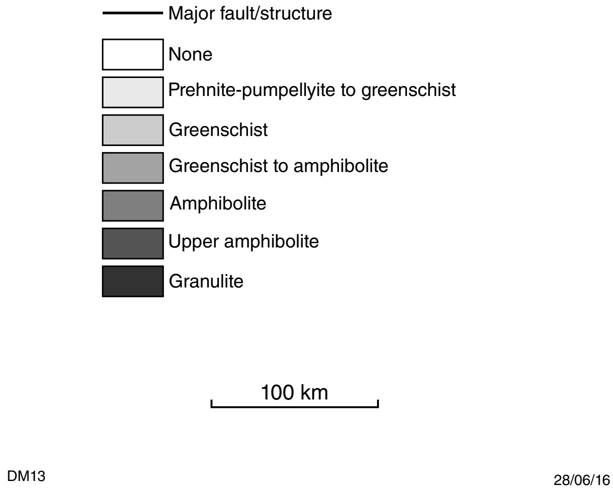


Figure 12. a) Map of regional metamorphic grade of units deformed and metamorphosed during the Hooper Orogeny; b) map of regional metamorphic grade of units deformed and metamorphosed during the Halls Creek Orogeny; c) map of metamorphic grade of units from the Eastern, Central, and Western Zones of the eastern Lamboo Complex. Metamorphic maps a), b), and c) are overlain with the structural–geophysical interpretation by Lindsay et al. (2015).

trending belt of the Tickalara Metamorphics in the central part of the Central Zone (Bodorkos et al., 1999). These granulite facies rocks and migmatites were deformed and metamorphosed at high grade during both the Hooper and Halls Creek Orogenies (Bodorkos et al., 1999). Rocks surrounding this elliptical high-grade domain were metamorphosed at lower grade (amphibolite facies) during both the Hooper and Halls Creek Orogenies, suggesting the possible presence of thrust imbricates separating these units of different metamorphic grade (Fig. 12).

Similarly, in the southern part of the Central Zone metasedimentary and granitic rocks of the Amhurst Metamorphics were metamorphosed at amphibolite to granulite facies during the Hooper Orogeny, but only to greenschist facies during the Halls Creek Orogeny. This supports the presence of deep penetrating faults and shear zones that exhumed these units into greenschist facies stable conditions between the Hooper and Halls Creek Orogenies.

Regional-scale geodynamic throttle, fertility, and deposition

The Halls Creek Orogen records periods of the assembly of the Paleoproterozoic supercontinent Nuna or Columbia through the Hooper and Halls Creek Orogenies and accretion of the Central and Eastern Zones to the Kimberley Craton (Huston et al., 2012; Tyler et al., 2012). Effects of the assembly of the supercontinent Rodinia (1300–900 Ma [Li et al., 2008]) may also be inferred from the intrusion of c. 1177 Ma alkaline rocks in the region that host the Argyle diamonds deposit.

The fertility, geodynamic throttle, and depositional sites of different commodities or mineral systems types are most often intrinsically linked to the tectonic development of a region through time, which is related to cycles of supercontinent assembly and break up (see Groves and Bierlein, 2007; Cawood and Hawkesworth, 2013). Specific tectonic triggers or a geodynamic throttle are required to form a mineral deposit. Such triggers could include subduction, changes in plate motion, magmatism into a region, compression along an arc section, topographic flow via fluid pressure gradients, or a specific dynamic threshold barrier (e.g. sills as opposed to dykes: Garwin et al., 2005; Gurney et al., 2005; Leach et al., 2005, 2010; Seat et al., 2007; Groves and Bierlein, 2007; McCuaig et al., 2010; Loucks, 2014). Fertility elements required for the development of valuable mineral or gem deposits could include magmas with mantle input, zones of repeated magmatic fractionation, hydrous magmas, CO_2 or F metasomatism, possibly driven by magmatic processes, salinity, oxidized fluids, oxidized or reduced magmas, and zones of juvenile magmatic input (Groves and Bierlein, 2007).

The tectonic evolution of the Halls Creek Orogen through time (i.e. geodynamic processes that influenced the formation of geological units in the region through time) is outlined above (see section **Tectonothermal evolution of the Halls Creek Orogen**) and is not repeated here. This interpretation forms the basis for defining the tectonic triggers that might have influenced ore formation in the region and thus have an effect on the regions prospectivity.

Some geological units within the Halls Creek Orogen have been outlined as being proxies for fertility for specific commodity groups (see additional data in zipped data files and predictor maps). However, these proxies are difficult to validate because they often are not directly associated with any known mineralization. Their relationship to supercontinent assembly and break up may be important, but this is sometimes difficult to evaluate due to conflicting interpretations and a paucity of data for regions formed in the Paleoproterozoic (Zhao et al., 2006; Ernst et al., 2008; Johnson, 2013; Evans, 2013). However, geochemical analysis of granitic and mafic–ultramafic igneous components (Sheppard et al., 1999, 2001; Griffin et al., 2000), the presence of different types of sedimentary rocks and basin analysis (Tyler and Griffin, 1990; Tyler et al., 1999, 2012; Blake et al., 2000; Hollis et al., 2014), and the age of different units relating to secular earth evolution are all critical to attributing relative fertility for the formation of different commodities. For example, sedimentary rocks deposited in the Western, Central, and Eastern Zones were all deposited after c.1870 Ma, after the great oxygenation event (Bekker et al., 2004). Thus, if they were deposited proximal to craton margins and deep-seated faults they could be prospective for clastic dominated, sedimentary exhalative, or replacement evaporate-style Pb–Zn deposits (Leach et al., 2005, 2010, 2013).

Fertility, geodynamic throttle, and deposition can be discussed in terms of three broad geological settings that include:

- intraplate, or passive margin settings, e.g. basin formation (in extension and compression), extension and rifting and plate reorganization during and after supercontinent assembly
- interpolate, e.g. convergence and transpressional setting — subduction and accretion of terranes, related to supercontinent assembly (e.g. Nuna/Columbia and Rodinia)
- divergence and break up, e.g. rifting and formation of LIP.

In the Halls Creek Orogen, only two of these — intraplate and interplate settings — have been interpreted. Even though the Hart Dolerite is thought to have formed as part of a LIP (Sheppard et al., 2012), it is still suggested that it developed due to post-convergence relaxation, leading to extension of the Kimberley Craton (Tyler et al., 2012). The fertility, geodynamic throttle, and deposition of different commodities in these two settings are discussed below.

Intraplate or passive margin settings

In the east Kimberley and within the Halls Creek Orogen, far-field tectonic processes such as subduction along distal plate margins during supercontinent formation, plate reorganization after supercontinent assembly, and rifting have influenced apparent intraplate processes that occurred over the Kimberley Craton and its margin throughout its Proterozoic history.

In this contribution, we refer to intraplate as areas that are a large enough distance from a plate margin to not be greatly affected by arc-magmatic processes or plate margin orogenesis. The Marboo Formation, Amhurst Metamorphics, Paperbark Supersuite, Whitewater Volcanics, Halls Creek Group, Speewah Group, and Hart Dolerite are all units that are thought to have formed in intraplate settings or rift settings. The Marboo Formation (including metamorphosed sedimentary equivalents in the Amhurst Metamorphics), lower Halls Creek Group (Ding Dong Downs Volcanics and Saunders Creek and Biscay Formations), and the Speewah Group were deposited in basins that developed in different tectonic settings over different cratonic margins and at different times — the Kimberley Craton (Marboo Formation and Speewah Group) and the North Australian Craton (Halls Creek Group) (Figs 2, 3, and 6). Whereas the intrusive and extrusive Paperbark Supersuite, Whitewater Volcanics, and Hart Dolerite formed along the Kimberley Craton margin and within the Western Zone of the Halls Creek Orogen.

Zn and Pb in sediment-hosted deposits

Zn and Pb are major components of clastic dominated (CD), evaporite replacement, and Mississippi-valley style deposits (Leach et al., 2005, 2010, 2013; Groves et al., 2010). The high metamorphic grade Broken Hill Pb–Zn–Ag deposit in New South Wales and the Mount Isa deposit in Queensland are considered to be CD deposits that developed in basins that formed in different tectonic settings (Huston et al., 2006; Leach et al., 2010). Pb–Zn with or without Cu deposits described to form in CD deposits have been shown to have formed in a wide range of tectonic settings (extensional and compressional Leach et al., 2005, 2010; Groves and Bierlein, 2007). However, in all Pb–Zn deposits reactivation of deep-seated extensional faults and close proximity to sutures between cratonic fragments may be necessary for their formation (Leach et al., 2005).

The Marboo Formation and the protoliths to the Amhurst Metamorphics were deposited between 1870 and 1865 Ma in a rifted continental margin setting and are prospective for Pb or Zn mineralization of the CD style. Within the Eastern Zone, stratiform Cu–Pb–Zn(–Ag–Au) mineralization is in the Biscay Formation (lower Halls Creek Group/Little Mount Isa prospect group, including the Ilmars base metal deposit) that formed in a passive continental margin over which sedimentary and mafic and felsic volcanic rocks were deposited on the western margin of the North Australian Craton. Within the Biscay Formation, the most prospective intervals are felsic volcanic and volcaniclastic rocks interbedded with chemical sedimentary rocks (chert, banded iron-formation, carbonate, volcaniclastic rocks and siltstone) in a CD setting (Sewell, 1999; Leach et al., 2010).

The overlying Olympio Formation (upper part of the Halls Creek Group) that may have formed in a foreland basin setting could also be prospective for sediment-hosted Pb–Zn deposits (Tyler et al., 1995, 1999; Sanders, 1999; Griffin et al., 2000; Hollis et al., 2014), specifically over areas that are cut by deep crustal-scale structures that formed during or prior to the deposition of the Olympio Formation. Prospectivity within the Olympio Formation may be higher in alkaline volcanic rocks contained within it as demonstrated by the c. 1850 Ma trachyandesitic volcanic rocks of the Butchers Gully Member, which is associated with known REE and Au mineralization in the region (Page and Sun, 1994).

In the Western Zone, the Speewah Group was deposited over the Paperbark Supersuite. There are no mineral deposits identified within the Speewah Group. However, base-metal mineralization associated with felsic volcanism appears towards the base of the unit.

Mississippi valley-type (MVT) deposits are the dominant carbonate-hosted mineral systems in the both the west and east Kimberley and in recent decades were mined on the Lennard Shelf (D'Ercole et al., 2000; Hassan, 2004). The MVT deposits in the Lennard Shelf are linked to fault-related dilation zones manifested in the region through an orthorhombic fault-fracture mesh (Dorling et al., 1997; Miller et al., 2007). In the northeast Kimberley, the Sorby Hills deposits formed in lower Carboniferous carbonate reef complexes of the Burt Range Formation (Bonaparte Basin) on the eastern edge of a basement high — the Proterozoic Pincombe Inlier (Ferguson, 1999). Also in this region, the Devonian Ningbing reef complexes contain MVT style mineralization that is preserved in a northwesterly trending horst block, oblique or orthogonal to the orogenic trend of the western Lamboo Province, which is consistent with models of mineralization utilized for the Lennard Shelf (Dorling et al., 1997; Miller et al., 2007) that overlies the Western Zone of the Lamboo Complex in the southwest of the region.

Au, Ag, Cu, Zn, Sn, and W in felsic to intermediate magmatic rocks and associated chemical sedimentary rocks

Within the Western and Eastern Zones of the Halls Creek Orogen some granites and associated porphyries and volcanic rocks formed during periods of extension or perhaps rifting. These include the Paperbark Supersuite and possibly granites that form the basement to the Halls Creek Group in the Eastern Zone.

Granites, porphyries, and volcanic rocks of the Paperbark Supersuite may have formed as I-types on the subducting plate during the Hooper Orogeny, but distal to the zone of convergence (Griffin et al., 2000; Tyler et al., 2012). Hence, they are included in the intraplate section of this report. It is possible that the supersuite intruded into a zone of tensional stress within the Marboo Formation and therefore a region that had previously undergone rifting. Griffin et al. (2000) ascertained that granite of the Paperbark Supersuite contains a large proportion of older crust. This, and the intrusive relationship to the Marboo Formation, suggests that the granites may be partly derived from melting of Marboo Formation rocks (Griffin et al., 2000).

There are no documented mines or deposits within the Paperbark Supersuite. The formation of the Paperbark Supersuite in a region that may have been previously metasomatized above a subduction zone (Spratt et al., 2014) and its association with mafic rocks (e.g. mixing and mingling with mafic–ultramafic rocks) suggests that it may be locally mineralized. Occurrences of Sn and W are known to be in the granitic intrusive component of the Paperbark Supersuite, whereas the Whitewater Volcanics (Paperbark Supersuite) also reportedly contains occurrences of Au, Ag, Pb, Cu, Mo, and Zn.

The occurrences of Sn and W within Paperbark Supersuite granite are in a zone wedged between a major northerly trending and northwesterly trending, deep crustal-scale structure. These appear to be alluvial occurrences. Their distribution within and surrounded by rocks of K-rich granite of the Paperbark Supersuite suggests that they could be derived from it, although this requires further investigation (Fig. 14).

In the Eastern Zone, occurrences of Sn and W are documented by Sanders (1999) as being associated with pegmatite and veins of quartz, quartz-carbonate, and quartz-tourmaline. Many Sn–W occurrences in the Eastern Zone are associated with small late pegmatite dykes that may have intruded after the Halls Creek Orogeny (Sanders, 1999).

The Au, Ag, Pb, Cu, Mo, and Zn metal association and tectonic setting for the development of the Whitewater Volcanics suggests that mineralization took place in an epithermal (Sanders, 1999), rift-style setting west (inboard) of the Kimberley Craton margin. Documented mineral occurrences in MINEDEX are typically adjacent to faults that are shown to cut the Paperbark Supersuite, but may have been reactivated through time. Due to the mineral occurrences within the Whitewater Volcanics, including such a broad metal association, the analysis of this unit was undertaken in conjunction with the Cu–Au–Mo prospectivity model (see below).

The Koongie Park Formation metasedimentary and felsic and mafic metavolcanic rocks are known to be associated with volcanogenic massive sulfide mineralization (Sewell, 1999) in the Central Zone (Fig. 15). Of particular interest are chemical sedimentary rocks of the Onedin Member of this formation, which are mineralized (Sewell, 1999). The formation was deposited between the Hooper and Halls Creek Orogenies at 1845–1840 Ma, during a period of plate reorganization and possible local transtension (Tyler et al., 2012). The development of the Koongie Park Formation over the Tickalara Arc and in a region that has been mapped as containing significant deep crustal-scale structures, suggests increased fertility in Cu, Pb, Zn, and Au (Tyler et al., 2012). Felsic porphyries in the region, such as the Angelo Microgranite are subvolcanic equivalents to the Koongie Park Formation (Sanders, 1999) and are associated with Cu–Mo–Ag–Au mineralization, formed in a probable intraplate rift setting (Baker, 2002) not related to magmatism within an arc.

Cu, Ni, PGE, V, and Cr in mafic and ultramafic rocks

Mafic and ultramafic rocks intruded the Paperbark Supersuite towards the end of, or just following, the Hooper Orogeny at c. 1850 Ma in a transtensional setting (Fig. 15; Tyler et al., 2012). These rocks both cut the Paperbark Supersuite and form net-vein and mingled textures within the granitic rocks, suggesting that they are at least in part contemporaneous with the Paperbark Supersuite. Mappable units of mafic igneous intrusive rock such as the Toby Gabbro, Corridor gabbro, and Springvale Suite appear to be spatially associated with northwesterly and northerly trending deep crustal-scale structures interpreted by Lindsay et al. (2016), suggesting that this structure in part operated as a magma conduit. The Toby Gabbro and Springvale Suite are described as subhorizontal sheet-like bodies (Shaw and Macaias, 2000) or sills. No mineral deposits are known within these units. However, their mafic to ultramafic geochemistry, sill-like geometry, presence in a region around orogen parallel, and orogen-normal deep crustal-scale structures suggests that they have the potential to host orthomagmatic Cu–PGE–V–Cr mineralization (Fig. 15).

The c. 1856 Ma Panton Suite forms a sequence of mafic–ultramafic layered intrusions in an area dominated by amphibolite facies rocks (Tickalara Metamorphics). The Panton Suite contains Ni–Cu–Co and PGE–Cr deposits.

The c. 1845 Ma Sally Malay Suite consists of mafic–ultramafic intrusions that are known to contain Ni, Cu, and Co resources (Hoatson and Blake, 2000) within magmatic sulfides, which are currently being mined at the Savannah and Copernicus deposits. The suite is situated in a region around and within the Tickalara Metamorphics and Sally Downs Supersuite proximal to large-scale, deep crustal-scale structures (reverse faults) that have juxtaposed the Tickalara Metamorphics metamorphosed to granulite facies against rocks of lower metamorphic grade (Fig. 16).

The c. 1790 Ma Hart Dolerite is a mafic intrusive sequence that forms a series of sills of dolerite, gabbro, and granophyre (Sheppard et al., 2012). The vast volume of mafic igneous rock in the Hart Dolerite is estimated to be c. 250 000 km^3,which suggests that it is part of a large igneous province (Sheppard et al., 2012) that formed after the termination of the Halls Creek Orogeny. Hollis et al. (2014) relate this period to orogenic collapse, so perhaps the intrusion of the Hart Dolerite is related to plate reorganization that triggered intracratonic magmatism (Tyler et al., 2012). Arndt et al. (2005) suggests that mafic magmas form in hot parts of the mantle, but those that are endowed with sulfides may be directly linked to contamination by sulfur-rich country rocks rather than interacting with sulfur sources at depth. On the southern and western margins of the Kimberley Basin and its contact with the Western Zone, the Hart Dolerite intrudes into sedimentary rocks of the Speewah Group and lower Kimberley Group. $^{143}Nd/^{144}Nd$ data for the granophyric portions of the Hart Dolerite, low Nb and Ta contents of the mafic units (Hollis et al., 2013), and units contact relationships indicate that it has undergone some crustal contamination (Sheppard et al., 2012).

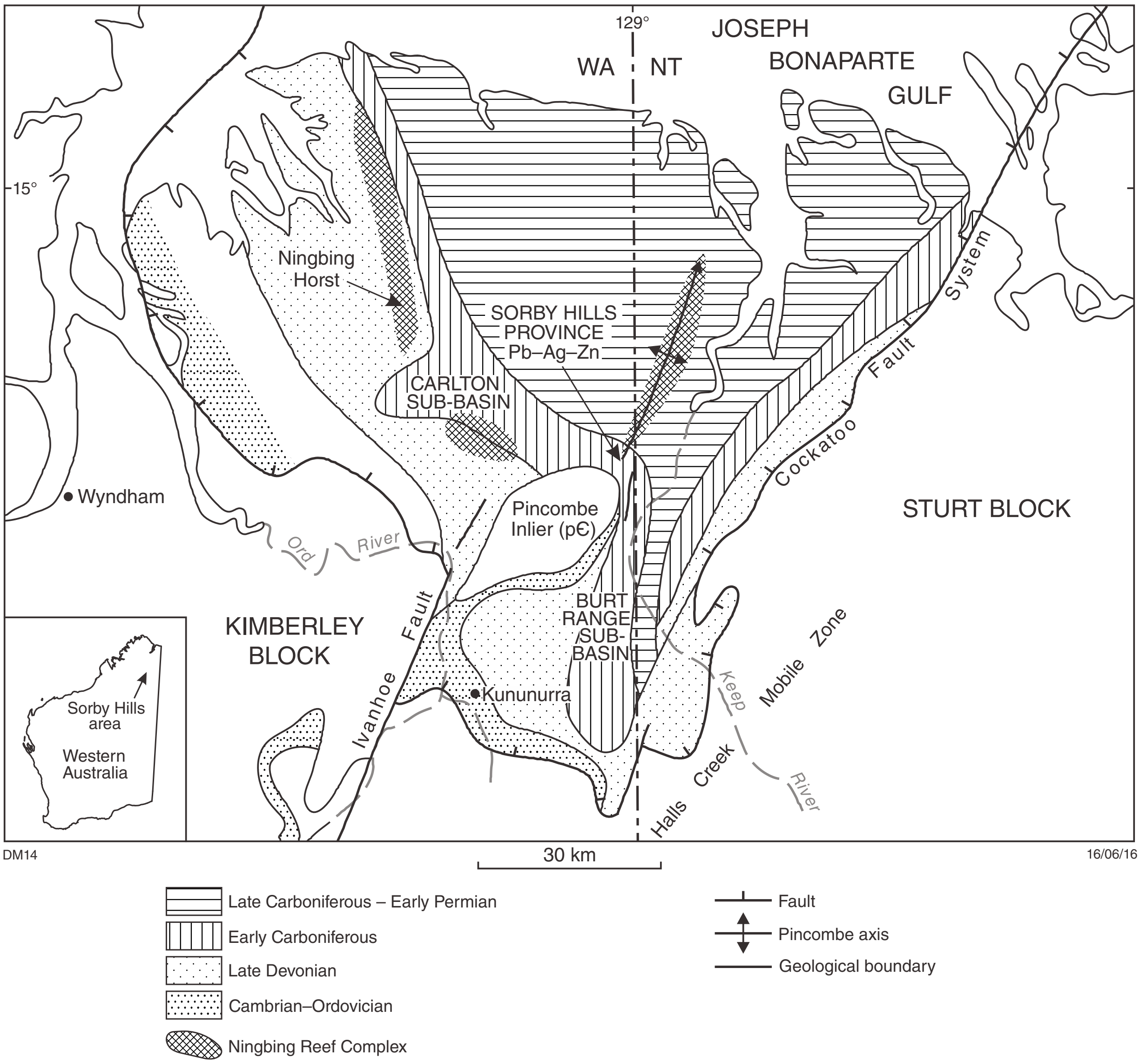


Figure 13. Simplified map of the Southern Bonaparte Basin, east Kimberley, illustrating the setting of the Sorby Hills deposits and the Ningbing reef complexes

At Speewah in the central to northern part of the Halls Creek Orogen, the Hart Dolerite forms part of the Speewah Dome, a north-northeasterly trending, doubly plunging, anticlinal structure that folds the sill complex. This area is host to Australia's largest magmatic V–Ti deposit (322 Mt @ 0.32%V_2O_5 and 2% Ti; King River Copper, 2015). V–Ti in magnetite is present within differentiated gabbro within the upper parts of layered intrusive bodies. In lower parts of layered intrusives, Cr–PGE may accumulate (Groves and Bierlein, 2007). These rocks may also be host to Ni–Cu sulfides (Cawthorn, 1996). At Speewah Dome the V–Ti is hosted by titanomagnetite in a 100 m thick magnetite-rich gabbro that is between a lower 300 m thick non-magnetic gabbro and overlying units of mafic to felsic granophyre. Within the magnetite gabbro most mineralization is in the lower 15–20 m with some accompanying increase in PGE over 0.1 m (PGE + Au c. 700 ppb; Andrew et al., 2012; Hollis et al., 2013). South of Speewah Dome, Fiorentini (2007) noted low levels of PGE in the Hart Dolerite sills, consistent with concentration of these elements in at least some late intrusive phases.

Diamonds

The Kimberley region contains the highest known concentration of diamondiferous magmatic intrusions in Australia. These intrusions include kimberlites, lamproites, lamprophyres, and carbonatites on and around the Kimberley Craton, which range in age from 1910 to 20 Ma (Jaques and Milligan, 2004). Commercial diamonds in the Halls Creek Orogen are mined from a lamproite intrusion at Argyle (AK1 olivine-lamproite pipe, eastern margin of the Central Zone, Halls Creek Orogen) that has been reported as the only major diamond pipe known in an early Proterozoic orogenic belt in the world (Luguet et al., 2009).

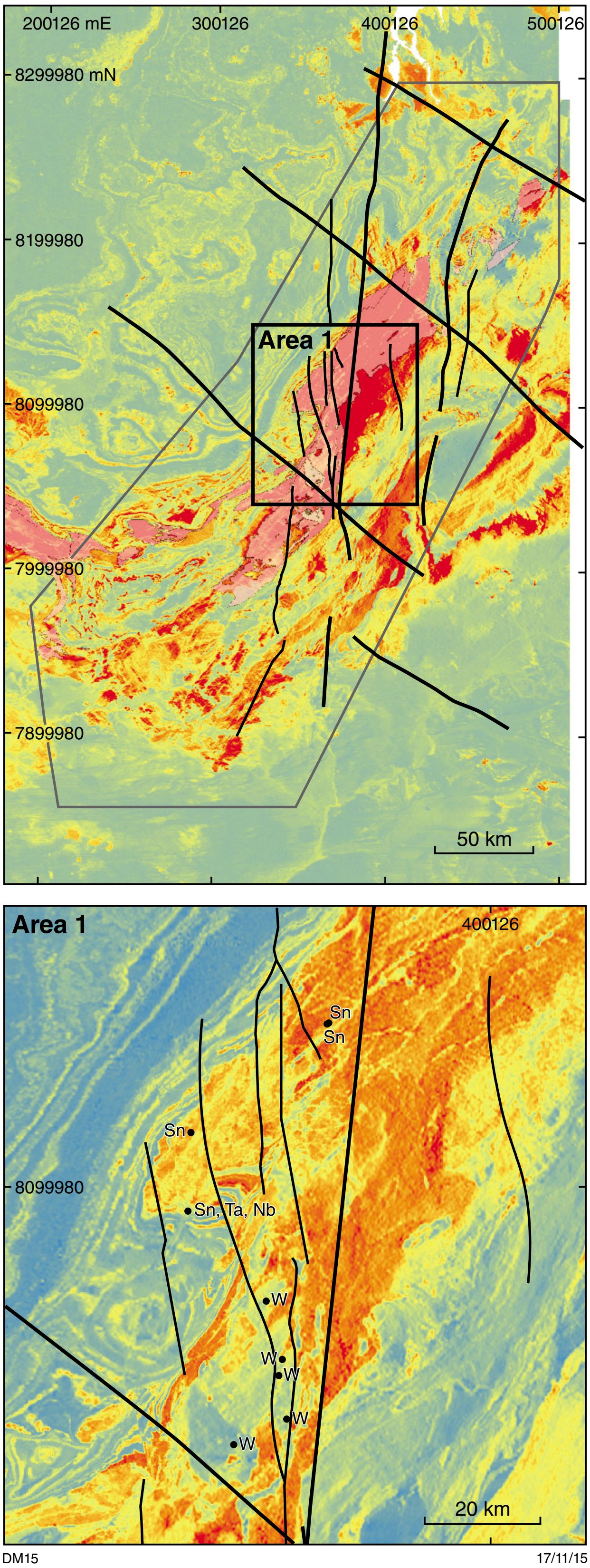


Figure 14. **Potassium radiometric image. Top – overlain by north and northwest trending structures in the region, mapped by Lindsay et al. (2015); bottom – inset area overlain by W, Sn, Ta, and Nb occurrences**

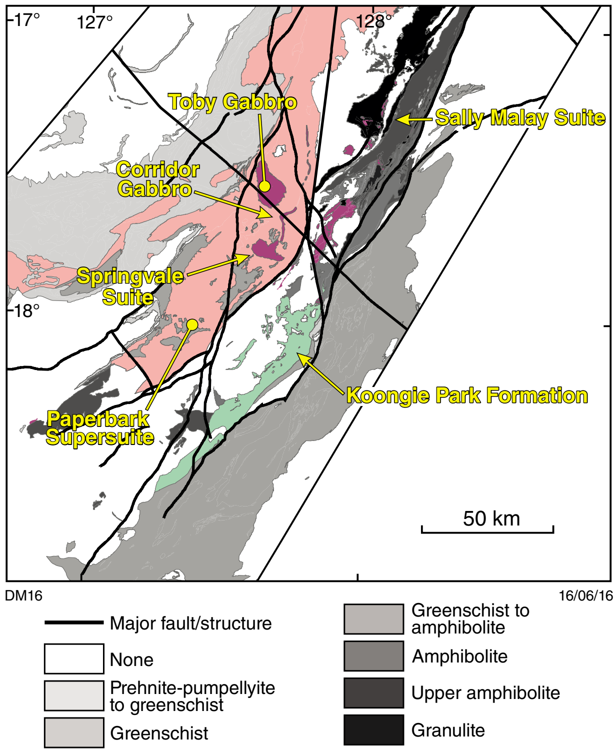


Figure 15. **Map showing the Paperbark Supersuite (pink), c. 1850 Ma mafic to ultramafic components (Toby Gabbro, Springvale Suite, and Corridor Gabbro), the c. 1845 Ma Koongie Park Formation, and the Sally Malay Suite**

The lamproite that hosts the Argyle deposit in the East Kimberley formed as a maar or diatreme. These form when magma rises and comes into contact with groundwater-bearing sediments, causing explosive subaerial volcanic activity (Lorenz, 1973). They have been described as forming large shallow craters (the actual maar) that can be up to 3 km wide and 300 m deep (Erlich and Hausel, 2009; Fig. 16). Therefore the footprint of a diatreme on the surrounding landscape can be much larger than the causative magma that impacted the sediments.

The Argyle lamproite has been dated at 1177 ± 47 Ma (Jaques et al., 1986; Luguet et al., 2009). Its age overlaps with the formation of the supercontinent Rodinia, the loosely constrained Yampi Orogeny (1400–800 Ma) recognized in the Kimberley region, and the Musgrave Orogeny (1220–1150 Ma) (Tyler and Griffin, 1990; Smithies et al., 2011, 2015). The occurrence of diamondiferous kimberlites and lamproites in the Halls Creek Orogen are summarized in Sanders (1999), who noted that they are spatially related to major faults in the Orogen — including the Gap Fault (Argyle lamproite pipe) and the Greenvale Fault (Durack Range kimberlite).

Rhenium–Osmium (Re–Os) model ages for Argyle peridotite xenoliths contain a wide age range, from c. 3200 to 1100 Ma, with the largest population of Re–Os age data being between 2900 Ma and 2200 Ma

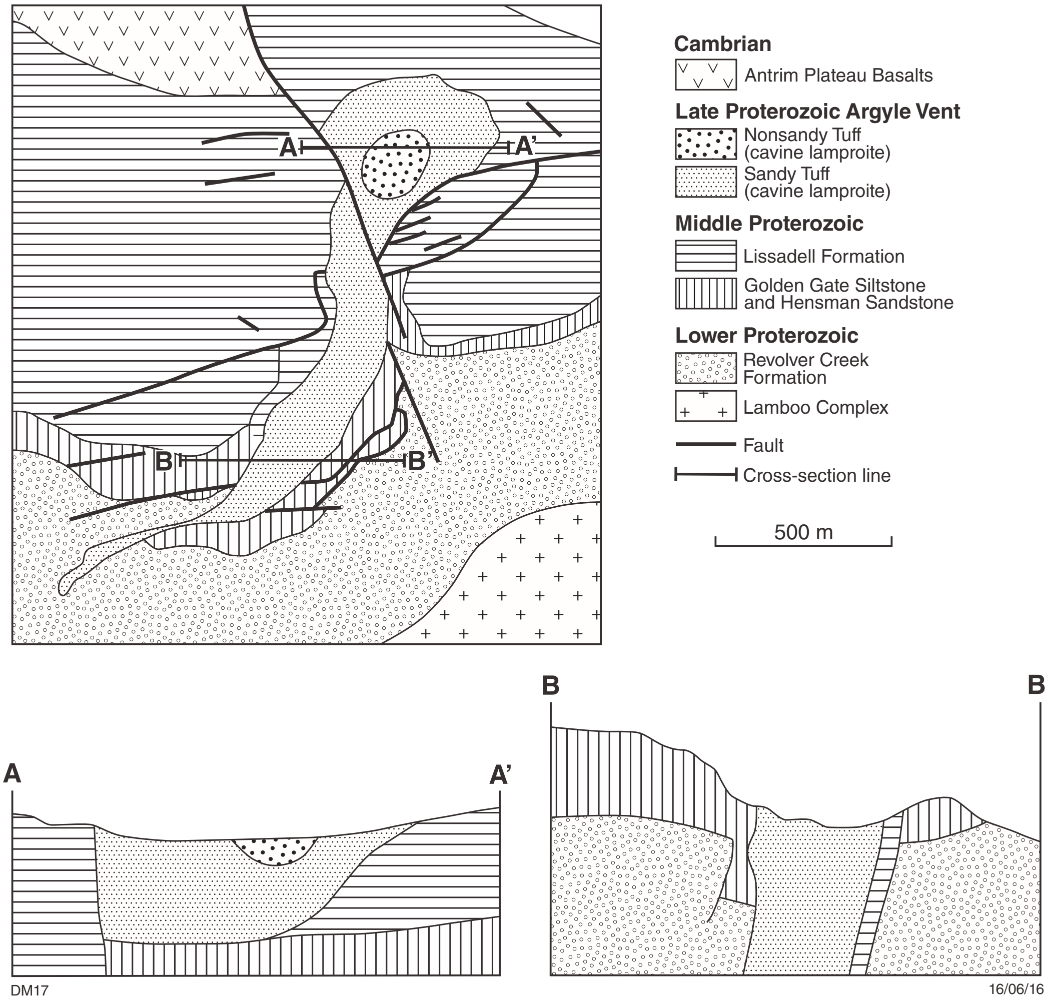


Figure 16. Model/geological sketch map and cross-section of the Argyle pipe, Western Australia from Erlich and Hausel (2009), modified after Mitchell and Bergman (1991)

(Luguet et al., 2009). However, the Re abundances within peridotite are not all primary, with some Re introduced by the c. 1177 Ma host lamproite (Luguet et al., 2009). This suggests that the Argyle lamproite has intruded through an Archean lithosphere, which is not exposed in the Halls Creek Orogen. The interpreted lithospheric root to the Halls Creek Orogen is inferred to be thick (between 200 and 250 km) based on thermobarometry on peridotite xenoliths from the Argyle pipe that were equilibrated within the diamond stability field (5 – 5.9 GPa, 1140–1290°C) (Jaques et al., 1990) and the current estimates of S-wave tomographic models in the region (Fishwick et al., 2005). The diamond xenocrysts are sourced from pre-existing upper mantle rock, such as the peridotite, eclogite, or websterite in the subcontinental lithospheric mantle (SCLM) and also occasionally (<1%) from lower than the SCLM in the mantle (e.g. majorite-bearing assemblages).

Magmas that carry the diamonds — kimberlite and lamproites pipes and lamprophyre dykes — use pre-existing structures in their ascent from the mantle into the middle to upper crust (Gurney et al., 2005). At the regional scale, these structures are thought to be contact zones between Archean cratonic roots (Griffin et al., 2009). In the Halls Creek Orogen the location of Argyle is close to the intersection of a major northeast- and northwest-trending deep crustal-scale structure, which may have formed as early as the Paleoproterozoic during convergence and subduction at the Kimberley Craton margin during the Halls Creek or Hooper Orogenies. Lamproite pipes that are present in the Halls Creek Orogen have intruded through a region that has previously undergone subduction as the diamonds contained within them are eclogitic diamonds (Jaques et al., 1990; Gurney et al., 2010), supporting the view that the structures that were utilized in order to carry the lamproites to the surface could have formed during subduction processes.

The chemistry of lamproites is distinctive and can be used as a vector to areas that may be prospective for diamondiferous deposits. Lamproites contain diopside, phlogopite, K–Ti richterite, leucite, sanidine, wadite, priderite, and/or olivine with minor perovskite, apatite, spinel, and ilmenite and thus contain relatively high Ni, Cr, Co, Sc, Ti, K, Mg, and F contents (Erlich and Hausel, 2009). They are typically low in Al_2O_3, CaO, and CO_2, and are silica-poor mafic, peralkaline, ultrapotassic igneous rocks that are enriched in Zr (500 ppm), Nb and Sr (>1000 ppm), Ba (>5000 ppm), and Rb (>150 ppm) (Erlich and Hausel, 2009). When lamproites undergo weathering, their unique geochemistry leads to the production of a suite of secondary minerals such as nontronite, smectite, and barite (Erlich and Hausel, 2009). The combination of this and anomalously high K, Ti, Ba, Zr, and Nb in soil geochemistry provide a useful tool for targeting lamproites. However, the lack of soil geochemistry data at the regional scale has precluded the use of all except potassium highlighted from regional-scale radiometrics data in the prospectivity analysis part of this study (see section Prospectivity Analysis).

Interplate settings — e.g. convergence and transpression — related to subduction and terrane accretion during supercontinent assembly (Nuna/Columbia and Rodinia)

The Halls Creek Orogen records periods of the diachronous assembly of the Paleoproterozoic supercontinent Nuna/Columbia through the Hooper and Halls Creek Orogenies and accretion of the Central and Eastern Zones to the Kimberley Craton (Huston et al., 2012; Tyler et al., 2012). The upper plates of subduction zones, which formed during convergence are demonstrated to be fertile for metals such as Cu, Au, and Mo (Groves, 2007; Sillitoe, 2008). Units that developed during convergence and collisional processes in the Halls Creek Orogen include:

- Protoliths to the Tickalara Metamorphics — mafic, sedimentary, and granitic rocks that developed in the Tickalara Arc over an east-dipping subduction zone during the 1870–1850 Ma Hooper Orogeny
- Granitic and mafic rocks of the Sally Downs Supersuite that formed in an arc-type setting over a west-dipping subduction zone.

Apart from these geological units, other rocks in the region that were deformed and metamorphosed during the Hooper or Halls Creek Orogenies may be prospective for orogenic Au mineralization (Groves and Bierlein, 2007). Nevertheless, the formation of Au ore zones and their preservation is most likely to be limited to rocks of low metamorphic grades (greenschist facies or lower) and has been demonstrated to be rare at higher metamorphic grades (Tomkins and Grundy, 2009; Tomkins et al., 2009).

Many proxies for fertility, geodynamic throttle, and depositional sites can be used in regions developed during plate convergence. These may include:

- potassium metasomatism
- sites of intersections of major lithospheric scale structures
- sinks in regional-scale tectonic fabrics
- fold hinge zones of antiforms.

Potassium metasomatism may be associated with alteration surrounding mineralizing systems formed during plate convergence and in areas where alteration signatures are broad enough, so that variations in potassium delineated from radiometric datasets may be used as vectors to mineralization (Airo and Mertanen, 2008; Morrell et al., 2011). However, the only seamless dataset for potassium in the region is the radiometric data and for the most part it cannot be used as a vector to mineralization due to data resolution and the inability to quantify regolith effects over alteration effects. Further work is required in order to utilize the potassium radiometric response adequately. Zones of structural complexity in the Halls Creek Orogen that may form depositional sites for mineralization are reported in Lindsay et al. (2016).

Cu–Au–Mo in igneous rocks

Sedimentary and mafic volcanic protoliths to the Tickalara Metamorphics developed in the Tickalara arc over an east-dipping subduction zone prior to being intruded by juvenile felsic granitic rocks of the Dougalls Suite during the 1865–1850 Ma Hooper Orogeny (Tyler et al., 2012). Granitic and mafic intrusive rocks of the Sally Downs Supersuite include crustally derived adakites (Sheppard et al., 2001), tonalites, and granodiorites that formed in an arc-type setting over a west-dipping subduction zone intruding into and across the Central, Eastern and Western Zones of the Lamboo Province.

Igneous rocks emplaced during subduction in both the Tickalara Arc and succeeding the Sally Downs Arc may have included porphyries prospective for Au, Cu, and Mo that develop in the upper crust (above about 6 or 7 km). The spatial distribution of these porphyries may depend on a number of contributing factors, including the dip of the subducting slab and the presence of major lineaments or structures (Sillitoe, 2008). Major lithospheric-scale structures in these regions may both influence the fertility of metal-bearing magmas (Loucks, 2014) and focus the injection of Cu–(Au, Mo) fertile magmas into certain regions of the over-riding slab (Garwin et al., 2005; White et al., 2014).

Elemental ratios from granitic rocks formed in the Tickalara Arc (Dougalls Suite) and the Sally Downs Arc (Sally Downs Supersuite) contain high Sr/Y ratios above 40 and V/Sc values greater than 10 (see data in Sheppard et al., 1997, 2001). These high values and the presence of hydrous minerals, such as hornblende and/or biotite suggest that these rocks formed from a hydrous melt (where elements such as Ti, Sc, and Y are partitioned into fractionating hornblende), which have been demonstrated to be relatively more prospective for Cu(+Au) ores that form above subduction zones (Hiroyasu et al., 2010; Loucks, 2014).

Higher dissolved water or higher pressures in a melt also influence the relationship between Al_2O_3 and TiO_2 in the resulting magma, leading to higher Al_2O_3/TiO_2 ratios (above 25) in magmas that have undergone magmatic differentiation required for the formation of copper ore-forming arc magmas (Loucks, 2014). Some granitic rocks of both the Mabel Downs and the Syenite Camp suites have Al_2O_3/TiO_2 values between 25 and 60, indicative of copper ore-forming arc magmas (geochemical data from Sheppard et al., 2001). Apart from these geochemical variations, arc-derived mineralized magmas are also often associated with magnetic anomalism (high magnetic signature relative to background) within potassic alteration zones (Hoschke, 2011).

The Mabel Downs Suite (Sally Downs Supersuite) and Dougalls Suite (Tickalara Metamorphics) have been metamorphosed to amphibolite facies or transitional greenschist-amphibolite facies, suggesting that if porphyry- or epithermal-style deposits had been present in the upper crust they were exhumed and eroded, leaving behind the deeper roots of the magma system. Were these upper crustal components preserved they might be prospective for porphyry Cu–Au-related mineralization. Likewise, upper crustal porphyry components to the Syenite Camp Suite have not been reported in the region. This suggests that the rocks preserved may have formed at crustal levels too deep for the formation and preservation of Cu-bearing porphyry-style deposits, even if geochemical fertility indicators suggest that the magmas were Cu(–Au) fertile.

Au formed during orogenesis

In the Eastern Zone, metamorphosed felsic volcanic rocks and sedimentary rocks in the Halls Creek Group are known to contain Au. The gold mineralization may have taken place some time between 1810 and 1780 Ma (Sanders, 1999), in the late stages of the Halls Creek Orogeny, during and subsequent to the accretion and collision of the Eastern Zone onto the Central Zone of the Halls Creek Orogen. Locally, in the southern parts of the Central and Western Zones, Au occurrences have been reported (Sanders, 1999). The accumulation of gold ore in the Eastern Zone is structurally controlled and often appears to be associated with fold hinge zones and kinks in the regional tectonic fabrics in the region, which is similar to the occurrence of gold mineralization in the Bendigo Goldfield in Victoria (Leader et al., 2013).

The location of mineralization associated with orogenesis is often related to the presence of major long-lived, crustal-scale structures, particularly around areas where orogen-parallel and orogen-normal faults intersect (McCuaig and Hronsky, 2014). Above or around these major structures, deflection of the dominant regional structural grain may take place leading to a marked difference in orientation of regional fold axial surfaces or foliations, facilitating the focus of fluid flow (McCuaig and Hronsky, 2014), and providing a structural trap for the accumulation of ore. Given this, structurally controlled Au mineralization in the region, although mainly known to take place in the Halls Creek Group, may not be limited to this unit. It is therefore possible that Au mineralization formed during orogenesis could happen in any of the geological units formed prior to the Hooper or Halls Creek Orogenies. However, this is most likely in regions that were metamorphosed at or below the greenschist facies and that are spatially adjacent to major lithospheric scale faults; even though preservation of Au deposits metamorphosed and deformed at high grade has been reported elsewhere (Tomkins and Grundy, 2009). For example, low metamorphic grade rocks of the Koongie Park Formation that were deformed and metamorphosed in the greenschist facies during the Halls Creek Orogeny may be prospective for Au, especially as the formation lies adjacent to major crustal-scale faults that developed during the Halls Creek Orogeny (Lindsay, 2015). This reasoning also holds for the Tickalara Metamorphics, Marboo Formation, or other elements affected by orogenesis in the region.

Prospectivity analysis

Mineral prospectivity modelling

The creation of mineral prospectivity maps plays an important role in regional exploration (Bonham-Carter, 1994; Carranza, 2009). The maps do not directly point to exploration targets but rather highlight areas where multiple geological features considered important in a mineral system coincide, defining areas for more detailed assessment. There are two different approaches to prospectivity mapping. Depending on the number and quality of known deposits, one can select a data-driven or knowledge-driven approach. Knowledge-driven models rely on geological concepts describing the formation of mineral deposits, while data-driven analyses examine and utilize the statistical relationships between the known mineral deposit locations and the spatially coincident geological, geochemical, or geophysical features.

Mineral systems analysis (Knox-Robinson and Wyborn, 1997; Wyborn et al., 1994) is now regarded as the preferred framework for effective exploration targeting (McCuaig et al., 2010; Joly et al., 2012, 2014). The approach recognizes that deposits are formed as a result of much larger Earth systems. These systems operate at different scales to focus mass and energy flux.

Mineral systems analysis may be readily coupled with a knowledge-driven approach to prospectivity mapping where the appropriate components of a mineral system are represented by the corresponding evidence (predictor) layers. In addition, knowledge-driven mineral prospectivity mapping is appropriate in greenfields regions where no or only few mineral deposits are known. In this regard, the Halls Creek Orogen could be considered a greenfields region for all the mineralization types analysed in this study, and for this reason a knowledge-driven approach has been used. Limitations to this approach include – but are not confined to – the degree to which the mineral system is understood and the difficulty in defining and assigning suitable mappable proxies across all the elements deemed important in the formation, deposition, and preservation of particular commodities or commodity groups.

Knowledge-driven, fuzzy logic, GIS prospectivity models

The modelling followed the steps described by Lindsay et al. (2015):

- identifying mappable proxies of key components of a particular mineral system

- generating predictor maps based on these proxies
- assigning map weights, class weights, and confidence factors to the predictor maps
- estimating fuzzy membership values for each predictor map
- generating a prospectivity model through the overlay of weighted predictor maps in a fuzzy inference network (Joly et al., 2012).

Expert knowledge of mineral systems found in the study area was used to assign the map and class weights and the confidence factors to the fuzzy predictor maps.

The selected fuzzy logic-based inference network models require several predictor maps to be assigned membership values based on a combination of objective datasets and subjective model components. Each predictor map represents a component of a particular mineral system. For example, a set of major deep penetrating faults, comprise the crustal-scale lithospheric architecture of the region that acts as a pathway for mineralized fluids. The fertile zones may then be characterized by a group of geological units, which can serve as the source of metals. Similarly, a metamorphic map has the potential to constitute a proxy for the preservation potential of a mineral system through time. The individual membership values ultimately represent the cell-by-cell weighting of a predictor map in the mineral systems model.

All of the predictor map class weights vary between 0.001 and 1 (1 being the most prospective). We have used a linear membership function, where w_j corresponds to class weight and x to the numeric value of the class (Equation 1).

$$w_j(x) = \begin{cases} 0.001 & x < x_{min} \\ \frac{x - x_{min}}{x_{max} - x_{min}} & x_{min} < x < x_{max} \\ 1 & x > x_{max} \end{cases} \qquad \text{Equation 1}$$

Most of the predictor maps describe the distance to prospective features. For these predictor maps, the class weights correspond to the increase in prospectivity with decreasing distance from an object of interest. Values decrease linearly with distance from the object of interest to the edge of a buffer zone, a cutoff distance beyond which the influence of a feature is negligible. Zero values were not assigned, as some of the fuzzy logic operators used in the inference network would render areas with one missing component of the mineral system (zero value) as unprospective. Similarly, the spatial density of features was used and linearly decreasing classes of the density function were assigned up to a cutoff value beyond which the density of features was considered unprospective. Categorical evidence layers such as metamorphic zones were also used.

Confidence factors were assigned to each predictor map based on its perceived ability to 1) define accurately the appropriate component of a mineral system and 2) image the component in a raster/map form. The perception of reliability is generally low where the data provide an imperfect proxy for the desired mineral system component.

Each value (fuzzy membership) on a predictor map is a product of the map weight, class weight, and confidence factor at each point. The overall membership in the fuzzy inference network corresponds to:

$$\mu_{\sim A_i} = m_i \times w_j \times cf_i, \text{ where } m_i \in \langle 0;1 \rangle, w_j \in \langle 0;1 \rangle, cf_i \in \langle 0;1 \rangle \qquad \text{Equation 2}$$

Seven prospectivity models partitioned by mineral/element associations were created: Au, Au–Cu–Mo, Pb–Zn–Cu–Ag, Ni–Cu–V–Ti–PGE, Sn–W–Mo, diamond, and REE. The models combine the predictor maps through a set of fuzzy operators to produce a final prospectivity map. All of the models were constructed within the ESRI ArcToolbox ModelBuilder environment and can be easily rerun with different map weights and confidence factors or fuzzy operators. Various ‘operators’ are available to facilitate the combination of different predictor maps in a fuzzy logic model (Bonham-Carter, 1994). In this study, the fuzzy OR, fuzzy algebraic SUM, and fuzzy algebraic PRODUCT were used. The fuzzy operators provide a means for emphasizing or moderating certain prospectivity factors (Joly et al., 2012; Lindsay et al., 2015).

Predictor maps

All information relevant to prospectivity analysis of the Halls Creek Orogen has been extracted from public domain sources (i.e. GSWA, Geoscience Australia) or derived from geophysical analyses described by Lindsay et al. (2016). A 100 m unit cell size was chosen for the predictor maps and the final prospectivity products. This selected resolution best represents the different available geophysical and geological data. The descriptor maps were divided according to the proposed mineral systems diamond schema, where the crustal-scale architecture represents the first branch of the fuzzy inference network, fertility the second branch, the third branch corresponds to the preservation component, and the fourth branch bins together the geodynamic throttle and deposition site. A different global map weight was applied to each branch reflecting its importance: fertility m_i = 0.9, crustal architecture m_i = 0.7, preservation m_i = 0.5 – 0, geodynamic throttle and deposition site m_i = 0.5. Confidence factors cf_i were attributed to each of the predictor maps based on the perceived reliability of the data and their ability to accurately define a particular mineral system component. Table 3 shows the classifications used, the confidence factors, and the map weights. It also depicts how the predictor maps were combined in the intermediate steps. The overall overlay product is a penalty function that returns the product of several fuzzy layers. It does not simply return the value of a dominant set (similar to the OR operator), but allows for combining all the values while penalizing pixels with low-fuzzy values. These aspects led to the choice of using the operator as the overall overlay method.

Table 3. Fuzzy inference network for Halls Creek Orogen prospectivity modelling. Note that the evidence weight quoted in bold is the map weight × the confidence weight. For example, the map weight for the mantle tapping faults (0.9) × lithospheric architecture confidence (0.7) = 0.63; Num. classes = number of classes for a predictor map; Class div. = class division; Max fav. = maximum favourability; Min. fav. = minimum favourability; Conf. fact. = confidence factor value for a predictor map; Fert. weight = fertility map weight; Lith. Arch. Weight = lithospheric architecture map weight; Dep. site/geod. throt. weight = depositional site/geodynamic throttle map weight; Pres. weight = preservation weight

	Predictor map	*Buffer*	*Num. classes*	*Class. div.*	*Max. fav.*	*Min. fav.*	*Conf. fact.*	*Fert. weight*	*Lith. arch. weight*	*Dep. site/ geod. throt. weight*	*Pres. weight*	*Fuzzy operator*	
Diamonds	Distance kimberlites lamproites (m)	15000	16	1000	1	0.001	0.9	0.81				OR	
	Structural complexity crust (km^{-2})	NA	11	0.05	1	0.001	0.5	0.45					
	Distance major structures intersections (m)	10000	11	1000	1	0.001	0.9		0.63				SUM
	Distance major structures N (m)	10000	11	1000	1	0.001	0.9		0.63			OR	
	Distance major structures NW (m)	10000	11	1000	1	0.001	0.8		0.56				
	Distance major structures NE (m)	10000	11	1000	1	0.001	0.7		0.49				
	Depth to Moho (km)	NA	4	5	1	0.001	0.8			0.4		OR	
	Central and Western Zone, Hart Dolerite, Speewah Group	10000	11	1	1	0.001	0.7			0.35			
Au	Woodward Dolerite (wd)	1000	3	1000	1	0.001	1.0	0.9				OR	
	Dougalls Suite (DO)	1000	3	1000	1	0.001	1.0	0.9					
	Olympio Formation (HCo)	1000	3	1000	1	0.001	1.0	0.9					
	Biscay Formation (HCr-mkq,- xbb-cc)	1000	3	1000	1	0.001	1.0	0.9					
	Sally Downs Supersuite (SD-xgn-og, -md-mgt, -xgg-og)	1000	3	1000	1	0.001	1.0	0.9					
	Tickalara Metamorphics (Tl)	1000	3	1000	1	0.001	1.0	0.9					
	Koongie Park Formation (ke)	1000	3	1000	1	0.001	0.8	0.72					
	Biscay Formation (HCr-mf,- xmo-mg)	1000	3	1000	1	0.001	0.8	0.72					
	Sally Malay Suite (SM)	1000	3	1000	1	0.001	0.8	0.72					
	Hart Dolerite (ha)	1000	3	1000	1	0.001	0.6	0.54					
	Marboo Formation (mr)	1000	3	1000	1	0.001	0.6	0.54					
	Speewah Group (SP)	1000	3	1000	1	0.001	0.6	0.54					
	Sally Downs Supersuite (SD-xg-o)	1000	3	1000	1	0.001	0.6	0.54					
	Sophie downs Suite (SO)	1000	3	1000	1	0.001	0.6	0.54					
	Amhurst Metamorphics (am)	1000	3	1000	1	0.001	0.4	0.36					

Table 3. continued

	Predictor map	Buffer	Num. classes	Class. div.	Max. fav.	Min. fav.	Conf. fact.	Fert. weight	Lith. arch. weight	Dep. site/ geod. throt. weight	Pres. weight	Fuzzy operator	
Au	Distance major structures intersections (m)	10000	11	1000	1	0.001	0.9		0.63				SUM
	Distance major structures N (m)	10000	11	1000	1	0.001	0.9		0.63			OR	
	Distance major structures NW (m)	10000	11	1000	1	0.001	0.8		0.56				
	Distance major structures NE (m)	10000	11	1000	1	0.001	0.7		0.49				
	Distance faults	5000	6	1000	1	0.001	0.6		0.42				
	Fault bends density (km^{-2})	NA	11	0.015	1	0.001	0.9			0.45		OR	
	Fault intersection density (km^{-2})	NA	11	0.005	1	0.001	0.8			0.4			
	Structural complexity (km^{-2})	NA	11	0.2	1	0.001	0.8			0.4			
	Geochemical reactivity contrast	NA	11	0.2	1	0.001	0.8			0.4			
	Rheological contrast	NA	11	0.2	1	0.001	0.8			0.4			
	Distance to fold axes (m)	5000	6	1000	1	0.001	0.7			0.35			
	Metamorphic zones	NA	4	NA	1	0.001	0.7				0.35		
Ni, Cu, Ti, V, PGE	Sally Malay Suite (SM-ap)	1000	3	1000	1	0.001	1.0	0.9				OR	
	Panton Suite (PT)	1000	3	1000	1	0.001	1.0	0.9					
	Paperbark Supersuite (PB)	1000	3	1000	1	0.001	0.8	0.72					
	Sally Malay Suite (SM-ogn,- xo-a)	1000	3	1000	1	0.001	0.8	0.72					
	Lamboo Province ultramafic (ap-LM)	1000	3	1000	1	0.001	0.8	0.72					
	Hart Dolerite (ha)	1000	3	1000	1	0.001	0.6	0.54					
	Lamboo Province mafic–ultramafic (xo-a-LM)	1000	3	1000	1	0.001	0.6	0.54					
	Sally Downs Supersuite (SD)	1000	3	1000	1	0.001	0.2	0.18					
	Tickalara Metamorphics (TI)	1000	3	1000	1	0.001	0.2	0.18					
	Distance major structures intersections (m)	10000	11	1000	1	0.001	0.9		0.63				SUM
	Distance major structures N (m)	10000	11	1000	1	0.001	0.9		0.63			OR	
	Distance major structures NW (m)	10000	11	1000	1	0.001	0.8		0.56				
	Distance major structures NE (m)	10000	11	1000	1	0.001	0.7		0.49				
	Fault bends density (km^{-2})	NA	11	0.015	1	0.001	0.9			0.45		OR	
	Fault intersection density (km^{-2})	NA	11	0.005	1	0.001	0.8			0.4			
	Structural complexity (km^{-2})	NA	11	0.2	1	0.001	0.8			0.4			

Table 3. continued

	Predictor map	Buffer	Num. classes	Class. div.	Max. fav.	Min. fav.	Conf. fact.	Fert. weight	Lith. arch. weight	Dep. site/ geod. throt. weight	Pres. weight	Fuzzy operator	
Cu, Au, Mo	Sally Downs Supersuite (SD)	1000	3	1000	1	0.001	0.4	0.36				OR	
	Syenite Camp Suite (SDS)	1000	3	1000	1	0.001	1.0	0.9					
	Whitewater Volcanics (PBww)	1000	3	1000	1	0.001	0.5	0.45					
	Distance major structures intersections (m)	10000	11	1000	1	0.001	0.9		0.63				SUM
	Distance major structures N (m)	10000	11	1000	1	0.001	0.9		0.63			OR	
	Distance major structures NW (m)	10000	11	1000	1	0.001	0.8		0.56				
	Distance major structures NE (m)	10000	11	1000	1	0.001	0.7		0.49				
	Distance faults (m)	5000	6	1000	1	0.001	0.6		0.42				
	Fault intersection density (km-2)	NA	11	0.005	1	0.001	0.8			0.4		OR	
	Structural complexity (km-2)	NA	11	0.2	1	0.001	0.8			0.4			
	Rheological contrast	NA	11	0.2	1	0.001	0.8			0.4			
	Metamorphic zones	NA	3	NA	1	0.001	0.7				0.35		
REE	Copperhead Igneous Complex (ch)	1000	3	1000	1	0.001	1.0	0.9				OR	
	Olympio Formation (Hco-xmf-m)	1000	3	1000	1	0.001	1.0	0.9					
	Red Rock Formation (rk)	1000	3	1000	1	0.001	1.0	0.9					
	Olympio Formation (Hco-xsn-fn, -mft, -mf)	1000	3	1000	1	0.001	0.8	0.72					
	Granite in Eastern Zone (gnl-LM)	1000	3	1000	1	0.001	0.5	0.45					
	Eastman Granite (ea)	1000	3	1000	1	0.001	0.5	0.45					
	San Sou Monzogranite (ss)	1000	3	1000	1	0.001	0.5	0.45					
	Syenite Camp suite (SDS)	1000	3	1000	1	0.001	0.5	0.45					
	Sophie Downs Suite (SO)	1000	3	1000	1	0.001	0.3	0.27					
	Distance major structures intersections (m)	10000	11	1000	1	0.001	0.9		0.63				SUM
	Distance major structures N (m)	10000	11	1000	1	0.001	0.9		0.63			OR	
	Distance major structures NW (m)	10000	11	1000	1	0.001	0.8		0.56				
	Distance major structures NE (m)	10000	11	1000	1	0.001	0.7		0.49				
	Fault bends density (km^{-2})	NA	11	0.015	1	0.001	0.9			0.45		OR	
	Fault intersection density (km^{-2})	NA	11	0.005	1	0.001	0.8			0.4			
	Structural complexity (km^{-2})	NA	11	0.2	1	0.001	0.8			0.4			
	Metamorphic zones	NA	4	NA	1	0.001	0.7				0.35		

Table 3. continued

	Predictor map	Buffer	Num. classes	Class. div.	Max. fav.	Min. fav.	Conf. fact.	Fert. weight	Lith. arch. weight	Dep. site/ geod. throt. weight	Pres. weight	Fuzzy operator	
Sn, W, Mo	Paperbark Supersuite (PB)	1000	3	1000	1	0.001	1	0.9				OR	
	Olympio Formation (HCo)	1000	3	1000	1	0.001	0.8	0.72					
	Granite in Eastern zone (gnl-LM)	1000	3	1000	1	0.001	0.5	0.45					
	Copperhead Igneous Complex (ch)	1000	3	1000	1	0.001	0.5	0.45					
	Sophie Downs Suite (SO)	1000	3	1000	1	0.001	0.3	0.27					
	Distance major structures intersections (m)	10000	11	1000	1	0.001	0.9		0.63				SUM
	Distance major structures N (m)	10000	11	1000	1	0.001	0.9		0.63			OR	
	Distance major structures NW (m)	10000	11	1000	1	0.001	0.8		0.56				
	Distance major structures NE (m)	10000	11	1000	1	0.001	0.7		0.49				
	Distance faults	5000	6	1000	1	0.001	0.6		0.42				
	Fault bends density (km^{-2})	NA	11	0.015	1	0.001	0.9			0.45		OR	
	Fault intersection density (km^{-2})	NA	11	0.005	1	0.001	0.8			0.4			
	Structural complexity (km^{-2})	NA	11	0.2	1	0.001	0.8			0.4			
	Geochemical reactivity contrast	NA	11	0.2	1	0.001	0.8			0.4			
	Distance to high K threshold boundary	5000	6	1000	1	0.001	0.8			0.4			
	Metamorphic zones	NA	4	NA	1	0.001	0.7				0.35		
Pb, Zn, Cu, Ag	Langfield Group (C-LA)	1000	3	1000	1	0.001	1	0.9				OR	
	Ningbing Group (D-NI)	1000	3	1000	1	0.001	1	0.9					
	Koongie Park Formation (ke)	1000	3	1000	1	0.001	1	0.9					
	Biscay Formation (HCr)	1000	3	1000	1	0.001	0.7	0.63					
	Speewah Group (SP)	1000	3	1000	1	0.001	0.6	0.54					
	Amhurst Metamorphics (am)	1000	3	1000	1	0.001	0.5	0.45					
	Bungle Bungle Dolomite (uu)	1000	3	1000	1	0.001	0.5	0.45					
	Galloping Creek Formation (D-Co)	1000	3	1000	1	0.001	0.5	0.45					
	Marboo Formation (mr)	1000	3	1000	1	0.001	0.5	0.45					
	Winnama Formation (wi)	1000	3	1000	1	0.001	0.5	0.45					
	Hart Dolerite (ha)	1000	3	1000	1	0.001	0.4	0.36					

Table 3. continued

	Predictor map	Buffer	Num. classes	Class. div.	Max. fav.	Min. fav.	Conf. fact.	Fert. weight	Lith. arch. weight	Dep. site/ geod. throt. weight	Pres. weight	Fuzzy operator	
Pb, Zn, Cu, Ag	Tickalara Metamorphics (Tl)	1000	3	1000	1	0.001	0.3	0.27				OR	
	Carson Volcanics (KMc)	1000	3	1000	1	0.001	0.3	0.27					
	Olympio Formation (HCo)	1000	3	1000	1	0.001	0.1	0.09					
	Distance major structures intersections (m)	10000	11	1000	1	0.001	0.9		0.63				SUM
	Distance major structures N (m)	10000	11	1000	1	0.001	0.9		0.63			OR	
	Distance major structures NW (m)	10000	11	1000	1	0.001	0.8		0.56				
	Distance major structures NE (m)	10000	11	1000	1	0.001	0.7		0.49				
	Distance faults	5000	6	1000	1	0.001	0.6		0.42				
	Fault bends density (km^{-2})	NA	11	0.015	1	0.001	0.9			0.45		OR	
	Fault intersection density (km^{-2})	NA	11	0.005	1	0.001	0.8			0.4			
	Structural complexity (km^{-2})	NA	11	0.2	1	0.001	0.8			0.4			
	Geochemical reactivity contrast	NA	11	0.2	1	0.001	0.8			0.4			
	Rheological contrast	NA	11	0.2	1	0.001	0.8			0.4			
	Metamorphic zones	NA	4	NA	1	0.001	0.7				0.35		

Fertility

In this study, the fertility parameter was tied to specific lithological units, following the pretence that the origin of metals and fluids is usually connected with different rocks (Fig. 17). The lithological units were derived from an updated geological map of the area where existing GSWA maps of different scales were combined into a harmonized dataset.

Apart from the diamond model, a buffer zone of 1 km was used to indicate the uncertainty in the exact lithological boundaries (Fig. 17). For diamonds, a buffer distance of 15 km was utilized around the mapped lamproite and kimberlite occurrences, which is considered conservative as kimberlite pipes often appear in clusters that can be about 50 km in diameter (Jaques, 1998). Confidence factors were assigned to different lithologies reflecting their perceived ability to act as either a source of fluids or a source of the metal in a particular mineral system. For diamonds, the fertility was also tied with the deep lithospheric architecture derived by Aitken et al. (2013). A kernel density function, which computes the density of interpreted lines in a circular neighbourhood of 20 km from the Australian Seismological Reference Model (AuSREM; Kennett and Salmon, 2012) was used to map the complexity of the lithospheric boundaries in the study area. Eleven classes were used with a class division value of 0.05 and a maximum value of 0.45. The fertility predictor maps were combined using the fuzzy OR operator so that the maximum value of each predictor map was passed further on in the inference network.

Crustal-scale architecture

The crustal-scale architecture is considered an essential component of all mineral systems models created in this study (Sillitoe, 2000; Grauch et al., 2003; Groves et al., 1998). Faults represent discontinuities along which fluids may easily migrate (Cox et al., 2001). The regional structural interpretation by Lindsay et al. (2016) was used as the source of line features to which distances were computed. The average orientation of the features was calculated. Structures identified as major mantle-tapping faults were divided according to their orientation into northerly, northwesterly, and northeasterly trending segments. The northerly oriented major faults were assigned the highest confidence factor (0.9), while the northwesterly striking orogen-normal structures were assigned a confidence factor of 0.8. The least confidence (0.7) was given to the northeasterly striking faults, because their existence was regarded less probable. A 10 km cutoff distance was applied as the limit beyond which the influence of a particular fault was considered negligible. For some models the remainder of faults was used too. Here the buffer distance was decreased to 5 km. The distance to faults maps weighted by their confidence factors were combined using the fuzzy OR operator. Of particular interest were also the intersections of major mantle-tapping faults (Fig. 18). A 10 km buffer was used for the distance to the intersections. At these locations, the fluid flux might be intensified and as such the corresponding distance map was combined with the structures utilizing the fuzzy algebraic SUM, which acts as an increase operator. The classes for all of the predictor maps describing the crustal-scale architecture corresponded to 1 km intervals.

Geodynamic throttle, depositional site

The geodynamic throttle and depositional parameters of mineral systems were grouped together because the predictor maps used as proxies overlap between the two components. For example, the fault bends may reflect a change in paleostress orientation but also act as favourable depositional zones. The fault bends density map (Fig. 19) was derived as kernel density of point features per km^2, representing major changes in orientation along fault lines. The density point features representing major changes in fault line orientations were calculated using a search neighbourhood of 10 km. A class division value of 0.0015 (resulting in 11 classes) was used along with a saturation value of 0.05 above which the maximum membership value of 1 was used. The intersections of non-major faults could represent significant damage zones where metal precipitation may take place. A density map of the intersections per km^2 was calculated using a 10 km search neighbourhood. Eleven classes were used with a class division value of 0.005 and a saturation value of 0.05. The final density map corresponds to the overall structural complexity calculated as the kernel density of all line features (lithological boundaries, faults, fold axes, and dykes). Here, 11 classes were again used with a class division value of 0.2 and saturation value of two. Locations with a dense structural framework are regarded as effective traps for mineralization.

Contacts between lithological units with differing rheological or geochemical reactivity properties are regarded as preferential trap sites (Brown, 2002). The rheological and geochemical contrast maps were created by assigning to each interpreted lithological unit a relative rheology and relative geochemical reactivity value (Fig. 20; Brown, 2002). Lithological contacts were then assigned a difference value of the respective rheological and geochemical reactivity properties of two adjacent units. Line density per km^2 was computed for contacts with contrast values larger than zero. A search radius of 10 km was applied while the lines were weighted by the corresponding contrast value.

Distance to fold axial surfaces was also used to indicate fluid trap zones. However, fold axes are not easily mapped, which resulted in a lower confidence value of this predictor map. The classes correspond to 1 km distance zones up to a buffer value of 5 km beyond which the influence is considered negligible.

For the Sn and W prospectivity model a distance to the 2.5% K content boundary was used as a predictor map as spatial correlations were observed for Sn and W mineral occurrences along this margin. Six classes were created with 1 km class intervals and a 5 km cutoff/buffer limit.

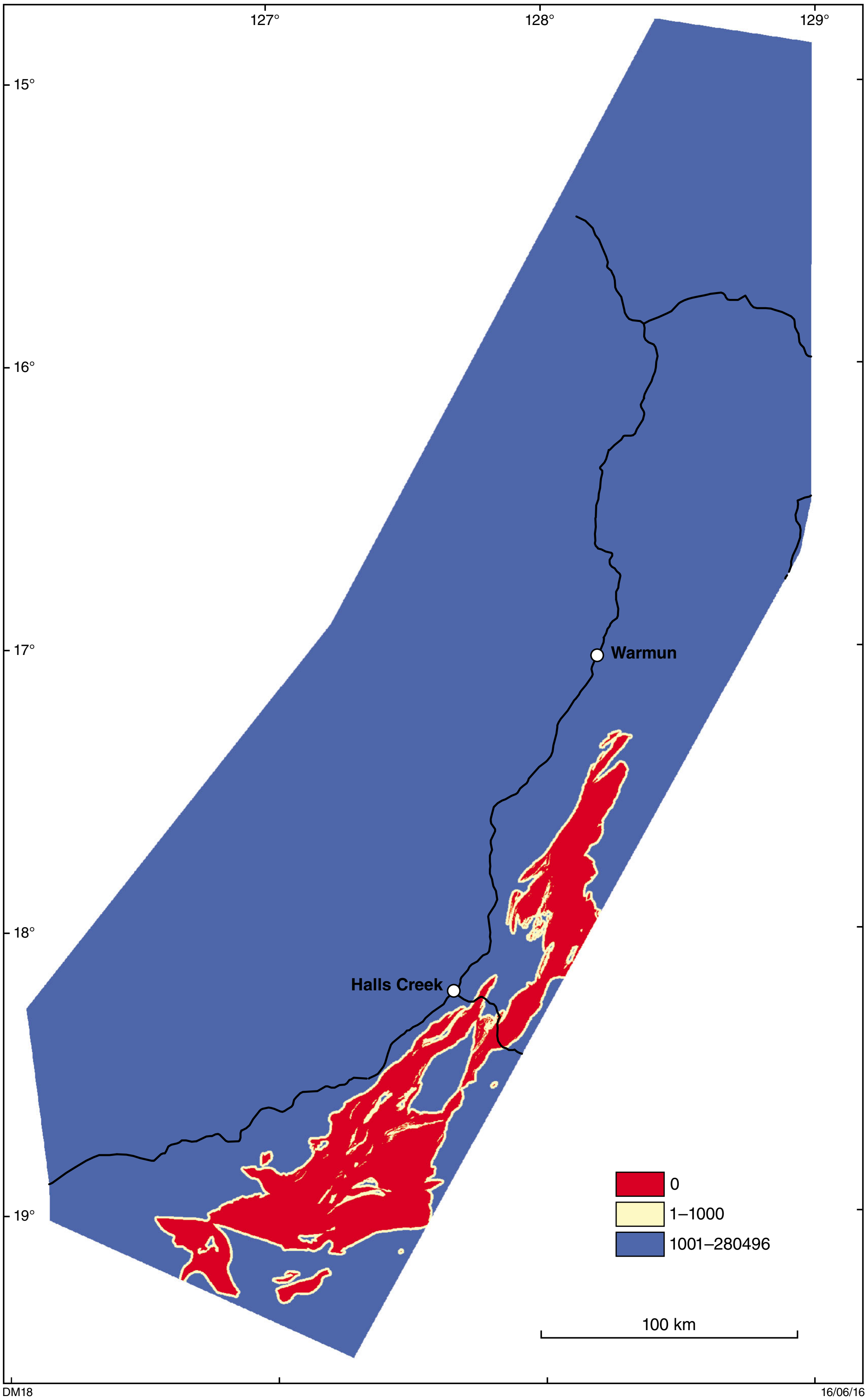


Figure 17. Presence of the Olympio Formation with a 1 km buffer used as fertility proxy to several prospectivity models, e.g. Au only, Sn–W–Mo, and Pb–Zn–Cu–Ag

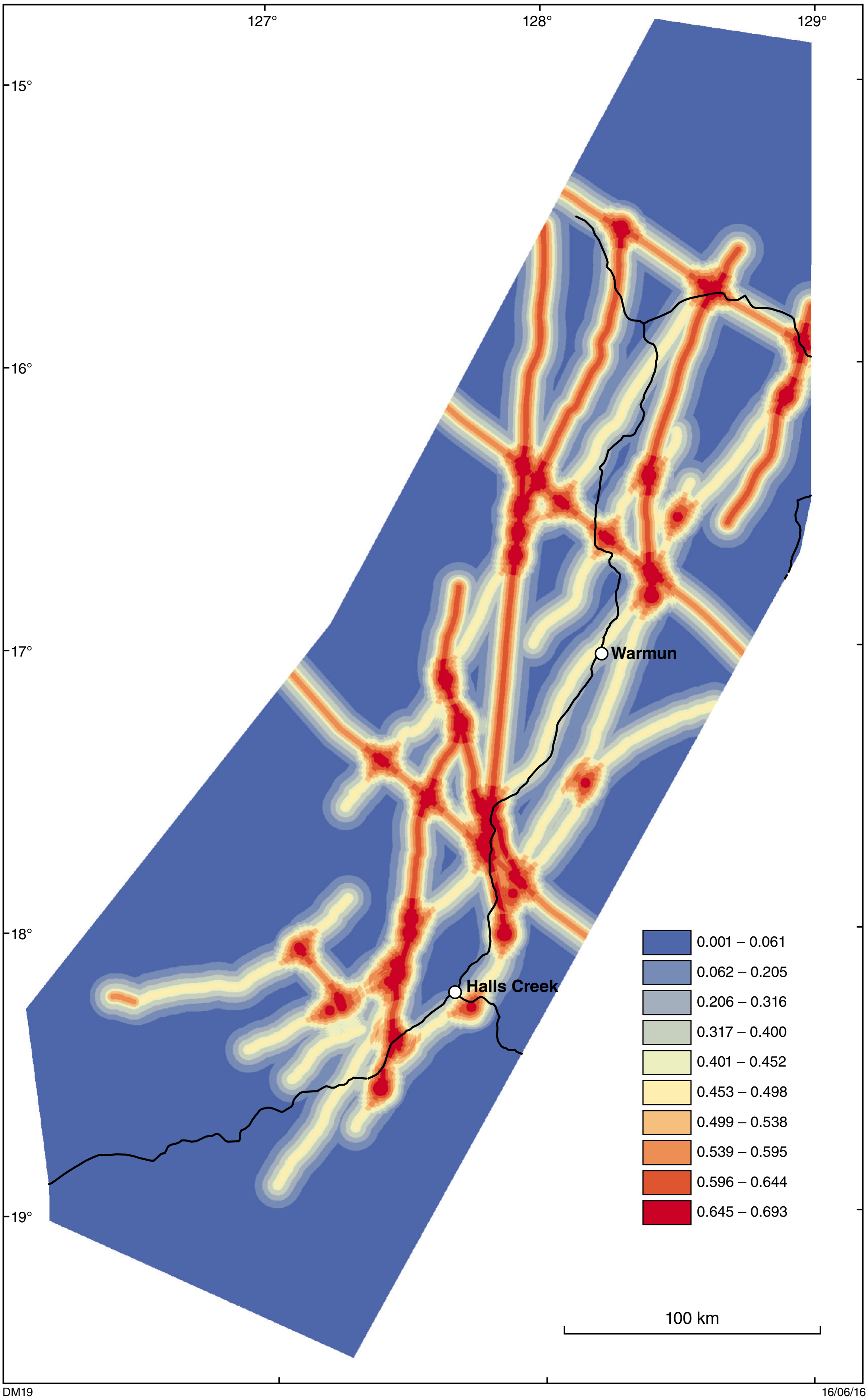


Figure 18. Representative map of fuzzy crustal architecture. A result of fuzzy algebraic SUM of distance-to-(major)-faults and distance-to-intersections

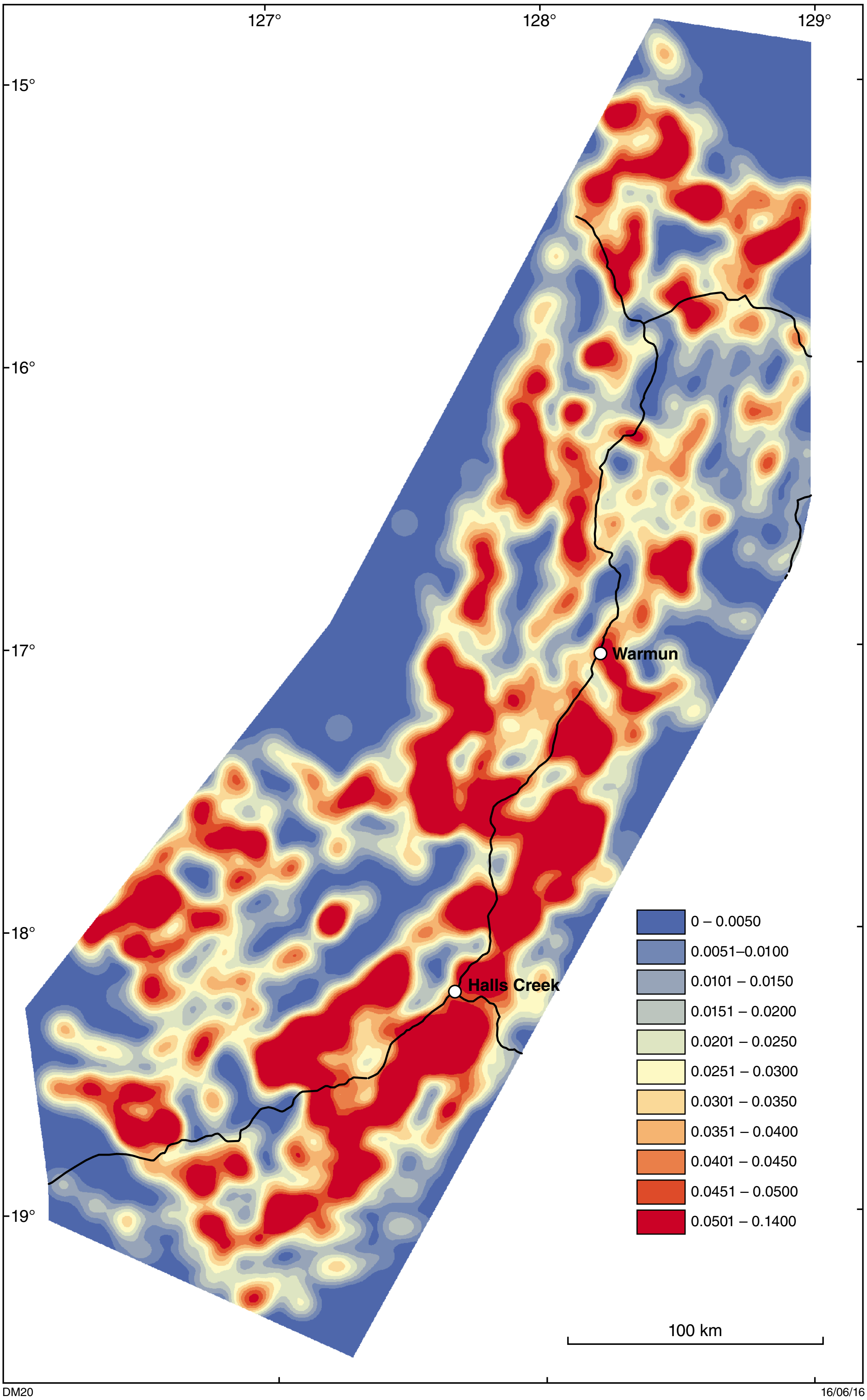


Figure 19. Fault bend density calculated as kernel density

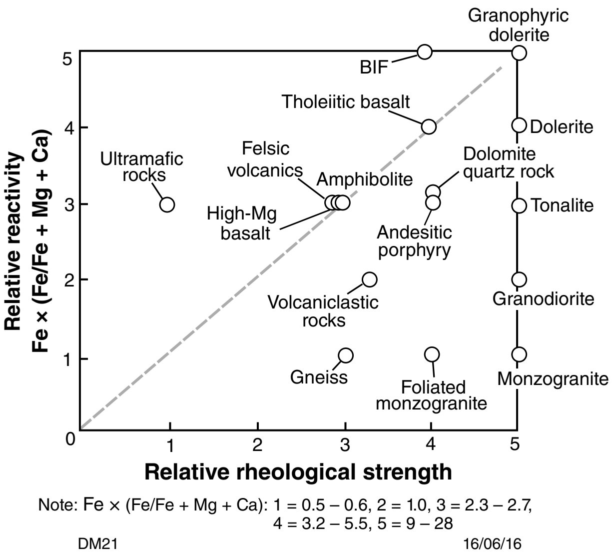


Figure 20. Relative chemical reactivity and rheological strengths for selected rocks (diagram developed from Brown, 2002)

The Moho elevation derived by Aitken et al. (2013) through joint inversion of gravity and magnetic data was used as a proxy to diamond depositional sites, as it is widely accepted that diamond-bearing kimberlite pipes are in zones of thick crust. Classes (Zones) divided by 5 km in depth were created. The highest membership value was assigned to the zones with lowest depth values. Apart from crustal thickness, tectonostratigraphic regions of the Halls Creek Orogen (Central and Western Zone and Kimberley and Speewah Basins) that are considered more prospective with regard to the occurrence of diamonds were used as a proxy to diamond depositional sites. A 15 km wide buffer zone was considered around these zones to account for the uncertainty in their actual borders.

Preservation

The preservation component may be important for certain commodity groups used in mineral systems analysis, such as Au and Cu–Au, while it may not play an important role at all in others, such as Ni–Cu–PGE (Fig. 10). The metamorphic map (Fig. 12) created during this study was used as a proxy for the preservation component of mineral systems. Different classifications were used for different mineral systems commodity groups (see Table 4). The higher the number assigned, the higher the fuzzy membership of the class in the model. The preservation component was not used at all for the diamonds model and the Ni–Cu–Ti–V–PGE model. A lower map weight of 0.3 was used in the Pb–Zn–Cu model as it is regarded as less important for the preservation of these mineral deposits.

Results and discussion

Mineral systems analysis for the Halls Creek Orogen was undertaken using a grouped commodities-based approach utilizing overarching features such as the presence or absence of deep crustal-scale structures, fertility, geodynamic triggers, depositional zones and preservation. Following this approach analyses for Sn–W, Cu–Au–Mo, Au only, Pb–Zn–Cu, Ni–Cu–PGE–V–Ti, REE, and diamonds were completed and are discussed below. Knowledge-driven input parameters for the prospectivity analysis used for the weighting of different evidence elements are summarized in Table 3.

Sn, W (and Mo)

Prospectivity mapping for areas most likely to be fertile for Sn and W focused on areas containing granitic rocks that formed in either an intraplate setting or distal from a subduction zone (Paperbark Supersuite) or in areas associated with documented pegmatite or veins of quartz, quartz–carbonate, and quartz–tourmaline associated with Sn and W and that may have intruded late in the Halls Creek Orogeny (Sanders, 1999). Molybdenum was also considered in this group, mainly because it is associated with Sn and W in the GSWA MINEDEX database. Parameters such as deep crustal-scale structures, structural complexity, and rock type or Zone (Western, Central or Eastern) were used to target for this commodity association. In doing this, it was found that the Eastern Zone, particularly in the south and regions in the Western Zone where deep crustal-scale structures intersect in areas that are intruded by granitic rocks of the Paperbark Supersuite, may be most prospective for Sn, W, and Mo mineralization (Fig. 21).

Table 4. Class values assigned to the metamorphic zones. Higher values correspond to higher prospectivity.

	Au	*Cu, Au, Mo*	*Sn, W, Mo*	*REE*	*Zn, Pb, Cu*
Granulite	0	0	0	0	0
Upper amphibolite	0	0	0	0	1
Amphibolite	0	0	0	0	1
Greenschist to amphibolite	1	0	1	1	1
Greenschist	3	1	3	3	2
Prehnite-pumpellyite to greenschist	2	2	2	2	2
None	1	2	1	1	3

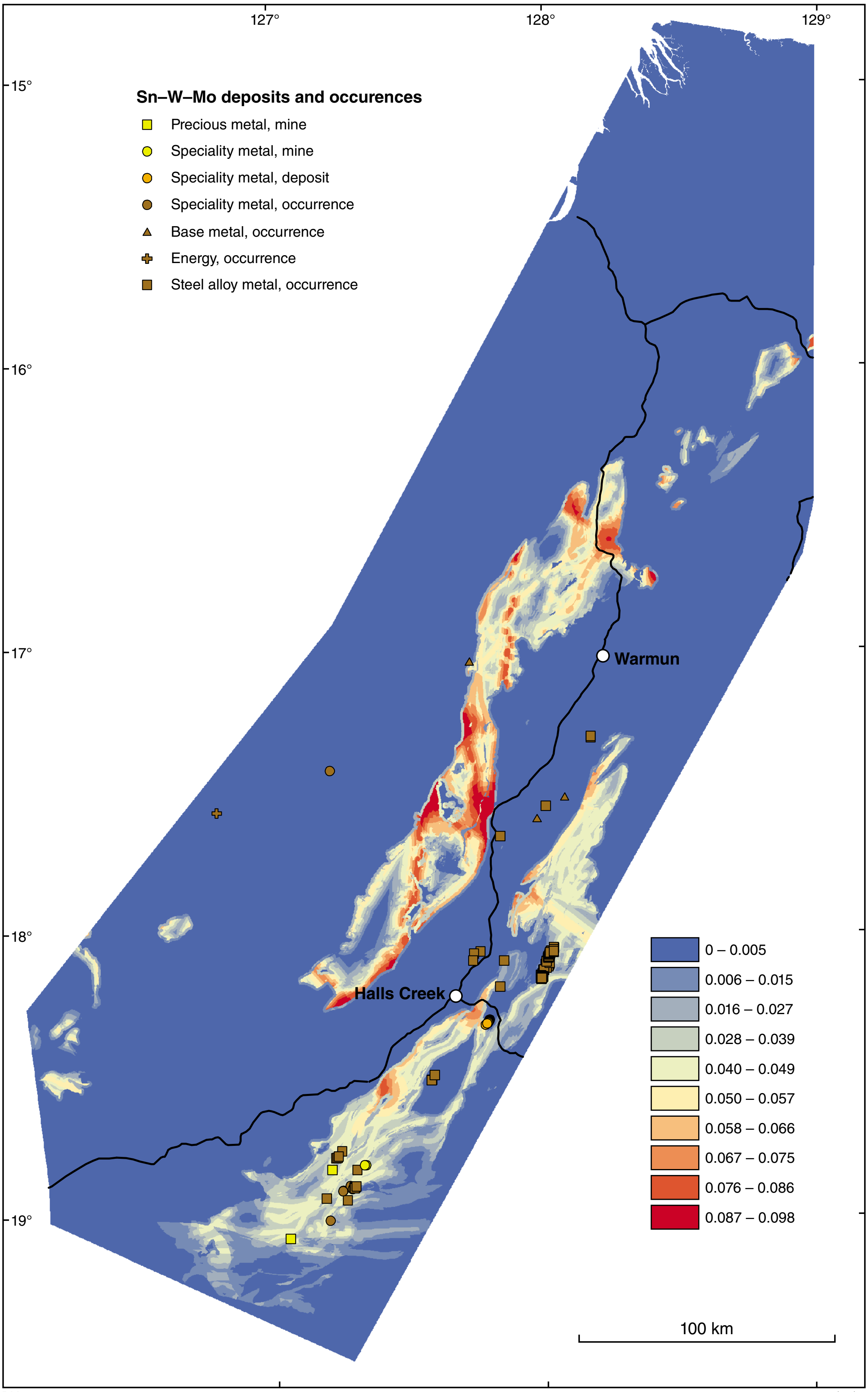


Figure 21. Prospectivity map derived for Sn–W–Mo

Rare earth elements

Rare earth elements include the 15 lanthanides and scandium and yttrium. Mineral occurrences of REE are mainly limited to the Eastern Zone, apart from one occurrence reportedly in the central part of the Central Zone associated with a carbonatite (Copperhead occurrence, MINEDEX Site Code S0024074). The single occurrence in the Central Zone is in a region that contains several intersecting deep crustal-scale faults mapped from gravity and magnetic data (Lindsay et al., 2016); whereas in the Eastern Zone, the Olympio Formation of the Halls Creek Group contains REE mineralization associated with c. 1848 Ma alkaline volcanic rocks (Blake et al., 1999) at the Brockman prospect.

Rare earth element occurrences are often associated with small stocks of alkaline intrusive rocks, but are most commonly found in carbonatites (Geological Society of London, 2011). In the Central Zone, an area mapped as Syenite Camp Suite was used as a proxy for a possible source region (at depth) for REE occurrences due to the younger Copperhead occurrence that is located within it. This occurrence is associated with intersecting northerly, northeasterly, and northwesterly trending fault zones (Fig. 22). As such the Syenite Camp Suite itself is not considered prospective for REE. The analysis highlights that REE distribution may most likely take place proximal to major faults, suggesting that they may extend into the Western Zone in areas of high structural complexity (e.g. around Speewah Dome). However, not enough is understood about the regional geological framework of the area with regards to the formation of REE deposits and the targeting mechanisms for this deposit style. This has limited the number of evidence layers permissible and is therefore producing limited results.

Co, Au, and Mo

Prospectivity with respect to Cu, Au, and Mo was considered in terms of mainly an interplate model for fertility, the proximity to deep crustal-scale structures, and preservation of upper crustal components in the present-day surface or subsurface. However, the Whitewater Volcanics were also included in this model whose formation may have been inboard of a plate margin, albeit on the downgoing plate of an interpreted subduction zone setting (Griffin et al., 2000). Specific areas within the Western, Central and Eastern Zones were all found to be prospective. However, the most prospective zone delineated through this analysis was in the central part of the Central Zone, in a part of the Syenite Camp Granite that is not considered to have undergone significant metamorphism and which lies over major deep crustal-scale structures (Fig. 23). Even though this region is considered prospective for porphyry-style Cu–Au–Mo mineralization, such mineralization has not been reported, nor have igneous intrusive rocks that formed in the roof zones of granitic intrusions been described. Thus the analysis may have highlighted a deep feeder zone to a porphyry system that is not preserved. Currently the sensitivity of the preservation component of the analysis is not well constrained enough to highlight differences in the upper few kilometres of the crust. More detailed analysis of the Sally Downs Supersuite (mapping and low pressure geothermometry) would be required to determine the present-day exposure level.

Au

An Au-only prospectivity analysis was completed in the region taking into account preservation level (using the proxy of metamorphic grade), rock type, fertility (areas that are considered to have developed above a subduction zone), connectivity to deep crustal-scale structures, complexity of structure, possible dilation zones, jogs in the dominant structural grain of the region and possible alteration zones (K-metasomatism). For this analysis, the formation and deposition of the Au is interpreted to have taken place during plate convergence.

The most prospective regions for Au-only mineralization were found to be in the Eastern Zone and some easternmost parts of the Central Zone (Fig. 24). Complexly deformed parts of the Central Zone were not considered to be prospective for Au mineralization because they were metamorphosed at high grade during both the Hooper and Halls Creek Orogenies.

In the Central Zone, the Syenite Camp Suite that is located adjacent to three deep crustal-scale structures may be prospective. However, this region appears as one of lowish prospectivity. This is because the Syenite Camp Suite in this area was not metamorphosed during the Halls Creek Orogeny, which is one of the criteria required for the Au-only analysis. Rocks of the deformed and metamorphosed (in greenschist facies) Koongie Park Formation are considered to be prospective for Au in zones of high structural complexity. In the Eastern Zone parts of the Biscay and Olympio Formations that are in regions of high structural complexity or areas around fault jogs that may be dilational zones, are considered the most prospective. The only area in the Western Zone that may be prospective for Au mineralization was found to be around the Speewah Dome, above the northerly trending deep crustal-scale structure. For all of these analyses all reported Au deposits and mines were captured (validated by MINEDEX; Fig. 24).

Pb, Zn, Co, and Ag

Areas containing small deposits and occurrences of base metals (including variable amounts of Pb, Zn, or Cu) are located in the southern part of the Central Zone within the Paleoproterozoic Koongie Park Formation, in the northernmost extent of the area in Devonian limestone reef complexes of the Ningbing Group preserved on the northwesterly trending Ningbing horst block, and in Carboniferous carbonates of the Southern Bonaparte Basin that developed around the flanks of the Proterozoic Pincombe Inlier (Figs 13 and 25). Occurrences of Devonian and Carboniferous Pb–Zn deposits are reportedly stratabound, forming in Mississippi Valley-type deposits (Dorling et al., 1997; Miller et al., 2007), whereas the Cu–Pb–Zn–Ag occurrences and deposits in the Koongie Park Formation formed as volcanogenic massive sulfides (Sanders, 1999; Sewell, 1999).

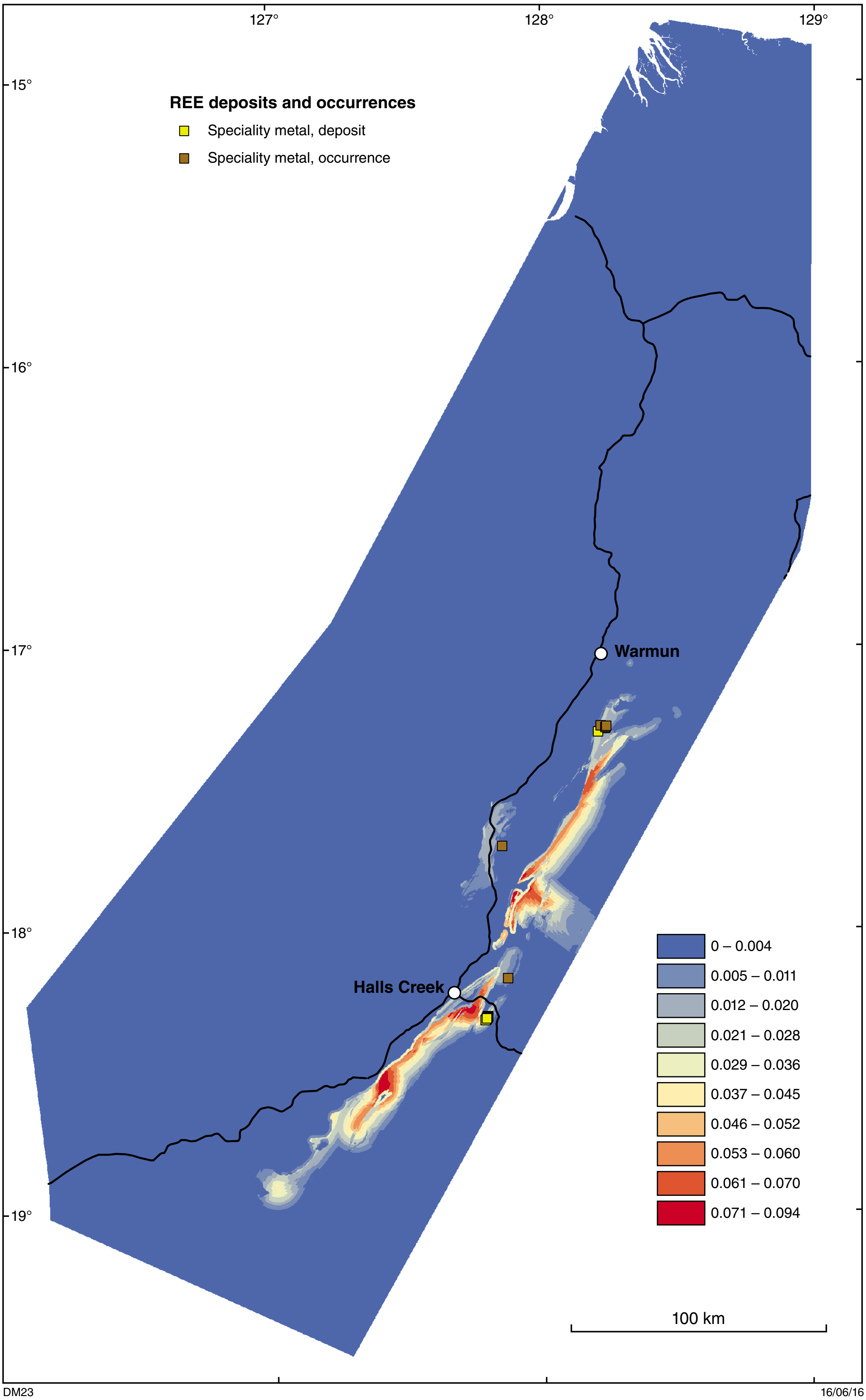


Figure 22. Prospectivity map derived for REE

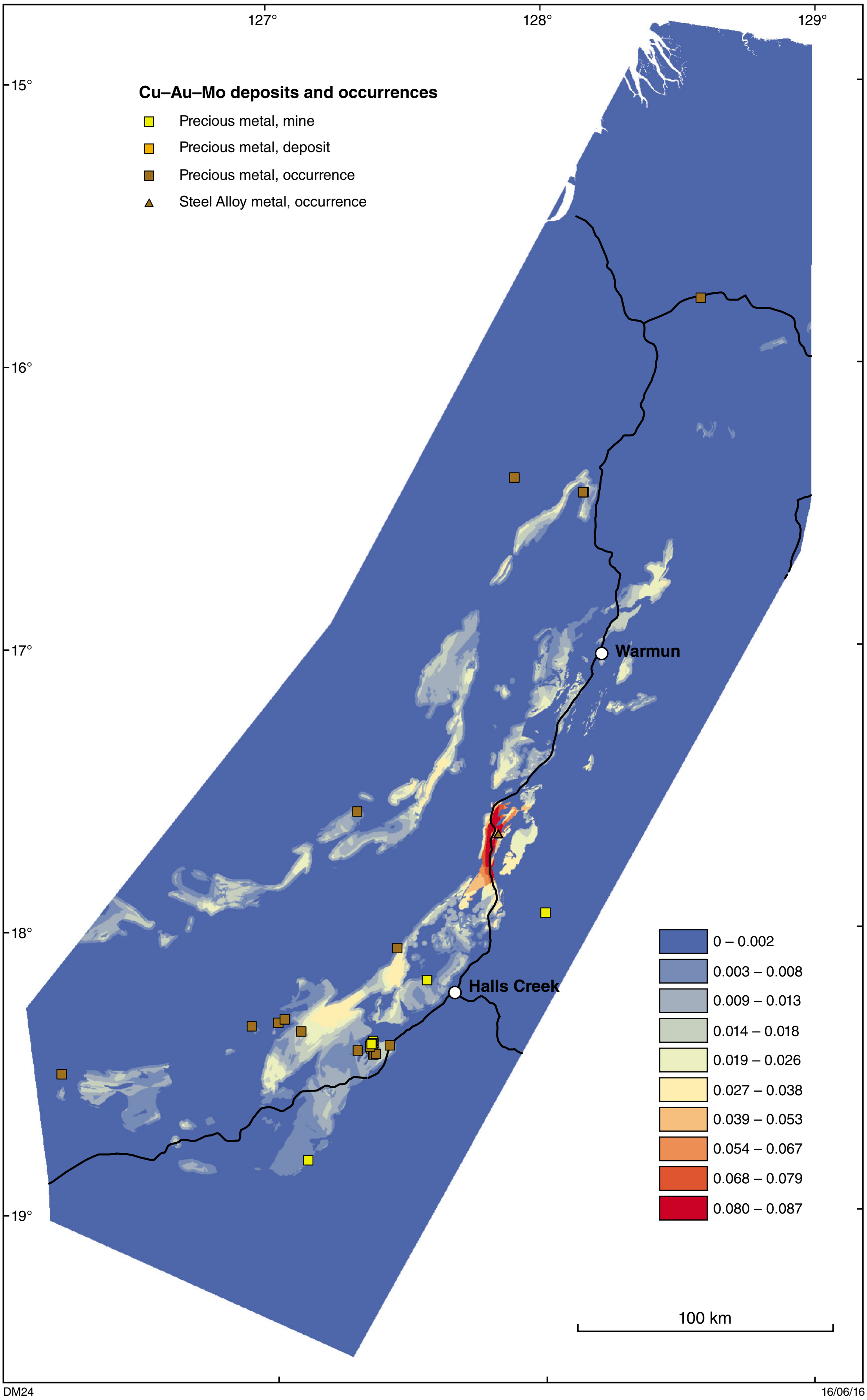


Figure 23. Prospectivity analysis for Cu–Au–Mo

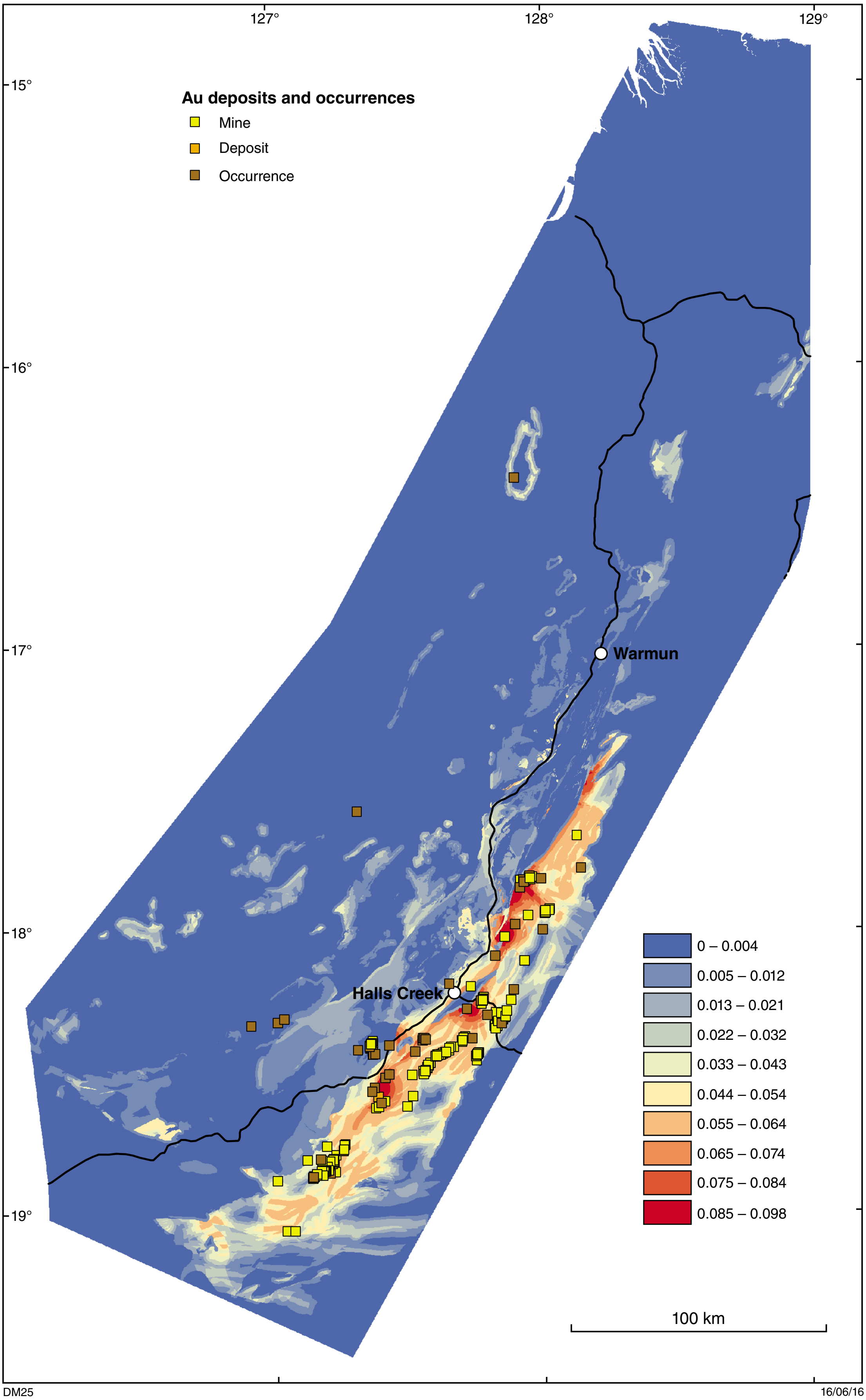


Figure 24. Prospectivity analysis for Au only

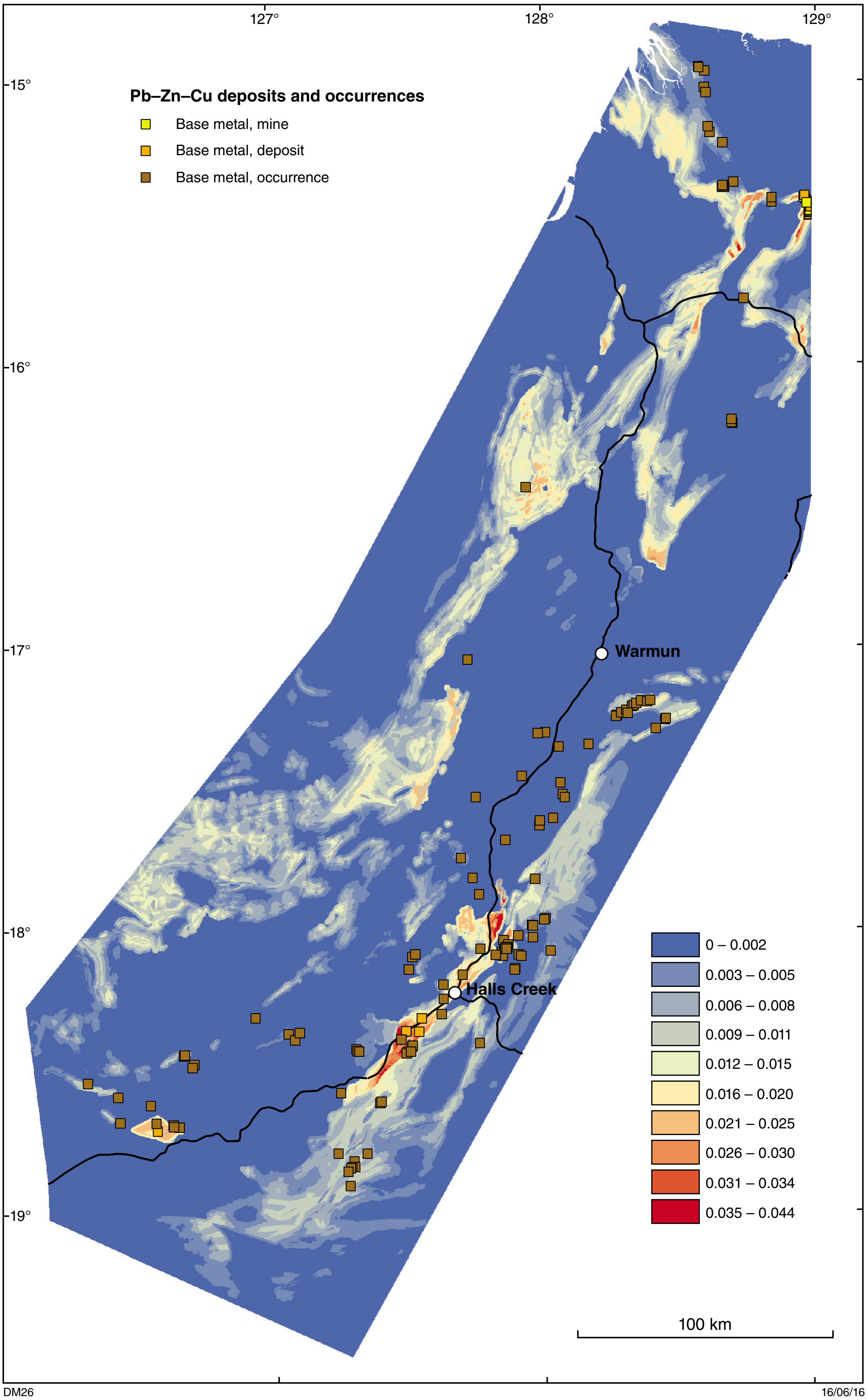


Figure 25. Prospectivity analysis for Pb–Zn–Cu–Ag

The prospectivity analysis outlined that areas of volcanosedimentary rocks of the Koongie Park Formation that are adjacent to deep crustal-scale structures are most prospective for Pb–Zn–Cu–Ag deposits, particularly adjacent to the Central–Eastern Zone boundary, and in the southern part of the Central Zone. In addition to this, all regions containing outcropping or regolith-covered occurrences of Devonian and Carboniferous carbonates, particularly adjacent to large-scale faults and basement highs, are prospective for Pb and Zn (Dorling et al., 1997; Miller et al., 2007). One region of particular interest includes an east-northeasterly trending part of the Paleo- to Neoproterozoic Bungle Bungle Dolomite in the central part of the eastern region of the study area, which was found to be slightly prospective for Pb–Zn.

In the southwestern part of the study area, the Bohemia zinc and Black Spur group of Pb–Zn prospects are in Devonian carbonate rocks that underlie the siliciclastic Permian Grant Group. These prospects were not highlighted in the prospectivity analysis, mainly due to the analysis being completed in 2D, with no reference to the Devonian carbonate sequences underlying the Grant Group. Further work is required to constrain these types of geological relationships in the region and to alter the workflow so that in completing the semi-automated prospectivity analysis such regions may be captured.

Parts of the Speewah Group in a triangular zone between northwesterly, northerly, and northeasterly trending major crustal-scale structures were found to be slightly prospective for base metal commodities. In this region, the high fault density and intersection of major structures could highlight the possible potential for base metal occurrences. However, none have been reported. The Tickalara Metamorphics in the Central Zone was not found to be prospective in this analysis even though there are reported occurrences of base metals from this unit. This is because the resolution of the mapping of the Tickalara Metamorphics used in this analysis was not high enough to include in the semi-automated prospectivity analysis completed here. Further work in this region may be required to assess the base metal potential of this unit.

Ni, Cu, Pt, Pd, Au, V, and Ti

The main influences on the prospectivity analysis for Ni, Cu, PGEs, Au, V, and Ti is the rock type in which it is assumed they will be deposited, and proximity to orogen-normal or northerly trending deep crustal-scale faults. For Ni, Cu, PGEs, Au, V, and Ti the most prospective rock types are those mapped as mafic to ultramafic in the region; thus, for this analysis the fertility and depositional site is essentially the same element. Mafic and ultramafic units that intruded during the c. 1850 Ma relaxation/extension event, such as the Panton Suite, Toby, Corridor gabbro, Springvale Suite, Sally Malay Suite and McIntosh Suite that intruded during the c. 1840 Ma pre-Halls Creek Orogeny extension or transpressional event, and some minor unnamed units are included in the analysis. In the analysis, areas where ultramafic to mafic rocks lie over orogen-perpendicular faults that cut the Halls Creek Orogen or the large-scale northerly trending fault that cuts through the Central and Western Zones were found to be most prospective for Ni, Cu, PGE, Au, Ti, and, V. As the deposition of these commodities in the crust is independent of the level of crustal exposure, features such as metamorphic grade do not influence the analysis (Fig. 12). The resulting prospectivity maps illustrate that mineral deposits and occurrences of the Ni, Cu, PGE, Ti, and V group have generally been captured in the automated prospectivity analysis (Fig. 26).

Diamonds

The Argyle Diamond Mine in the Halls Creek Orogen is a world-class diamond deposit formed in a lamproite pipe. However, most diamond occurrences in the east Kimberley region are alluvial diamonds, in which the source of the causative alkaline intrusive is unknown. For this analysis, a database of reported small alkaline stocks from throughout the east Kimberley compiled by GSWA (in prep.) was used as an input for the position of alkaline bodies that may or may not carry diamonds. In addition to this, depth to MOHO maps were used to indicate very deep crustal-scale structures, interpreted by analysing rapid changes in lithospheric thickness across the Halls Creek Orogen. The resulting prospectivity map illustrates that diamonds are most likely to have been deposited in the Central or Eastern Zones, along deep crustal-scale structures (preferably northwesterly or northerly trending) and proximal to alkaline intrusive bodies (Fig. 27). A northwesterly trending region of possible diamond prospectivity is highlighted in the southern part of the Halls Creek Orogen in which no alkaline bodies have so far been reported.

Conclusions

This study sought to develop models to characterize areas of mineral prospectivity for a group of seven commodities or mineral types of various ages and ore genesis mechanisms in the Halls Creek Orogen.

The work clarifies the extent of major structures and links the interpretation of Lindsay et al. (2016) with mineral systems analysis and the structural and tectonic history of the region, which is dominated by – but not restricted to – the Hooper and Halls Creek Orogenies.

The work assumed crustal-scale tectonic architecture, interpreted through geological–geophysical mapping and 2.5D magnetic and gravity modelling, is intrinsically linked to ore deposition, and therefore prospectivity. Through this work, we show that different tectonic 'Zones' of the Halls Creek Orogen are prospective for diverse commodity groups due to the tectonic environment in which they developed through time, the relative preservation zones conserved at the surface or subsurface, and favourable depositional sites that may be present in these 'Zones' (structural or lithological).

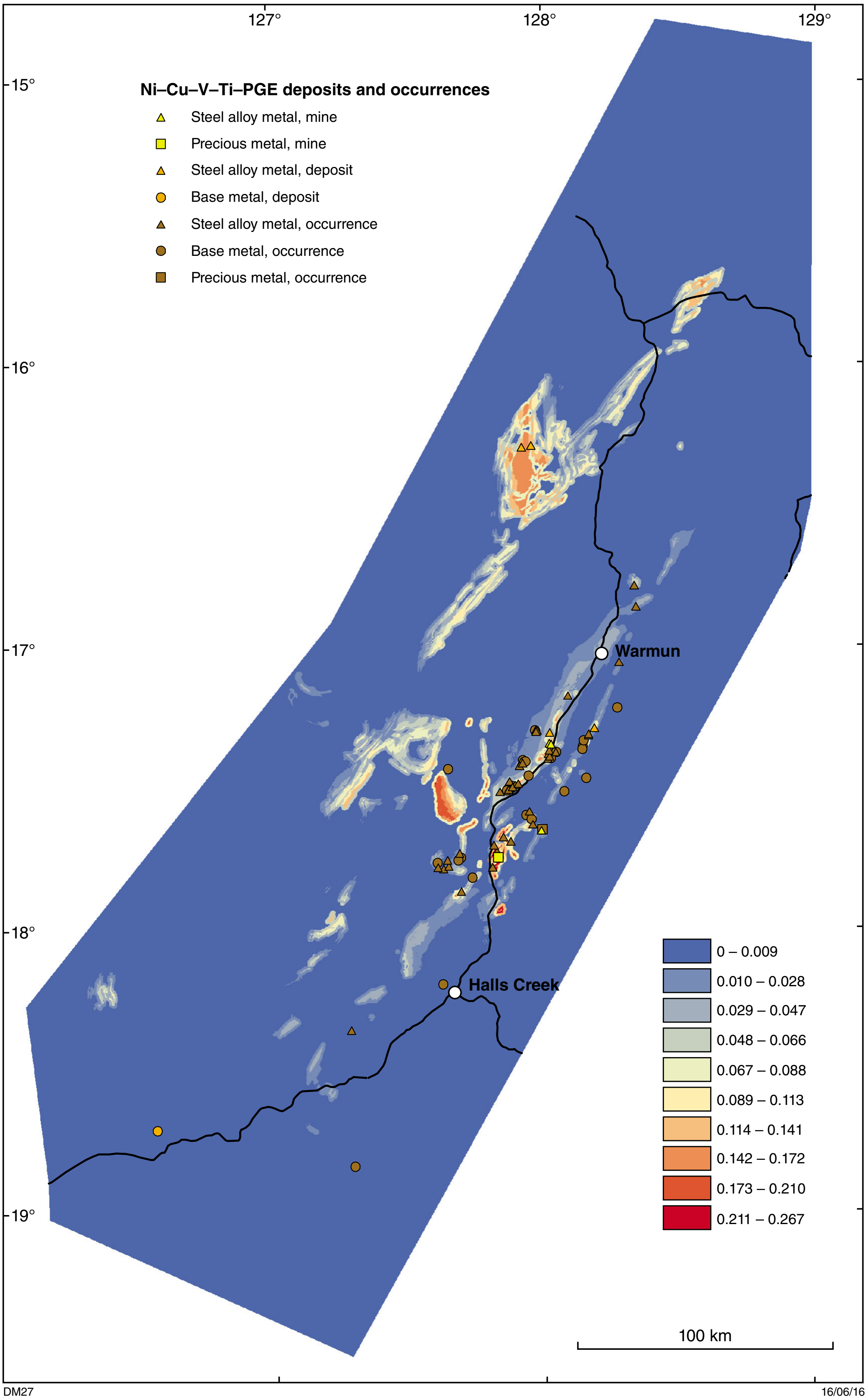


Figure 26. Prospectivity analysis for Ni–Cu–V–Ti–PGE

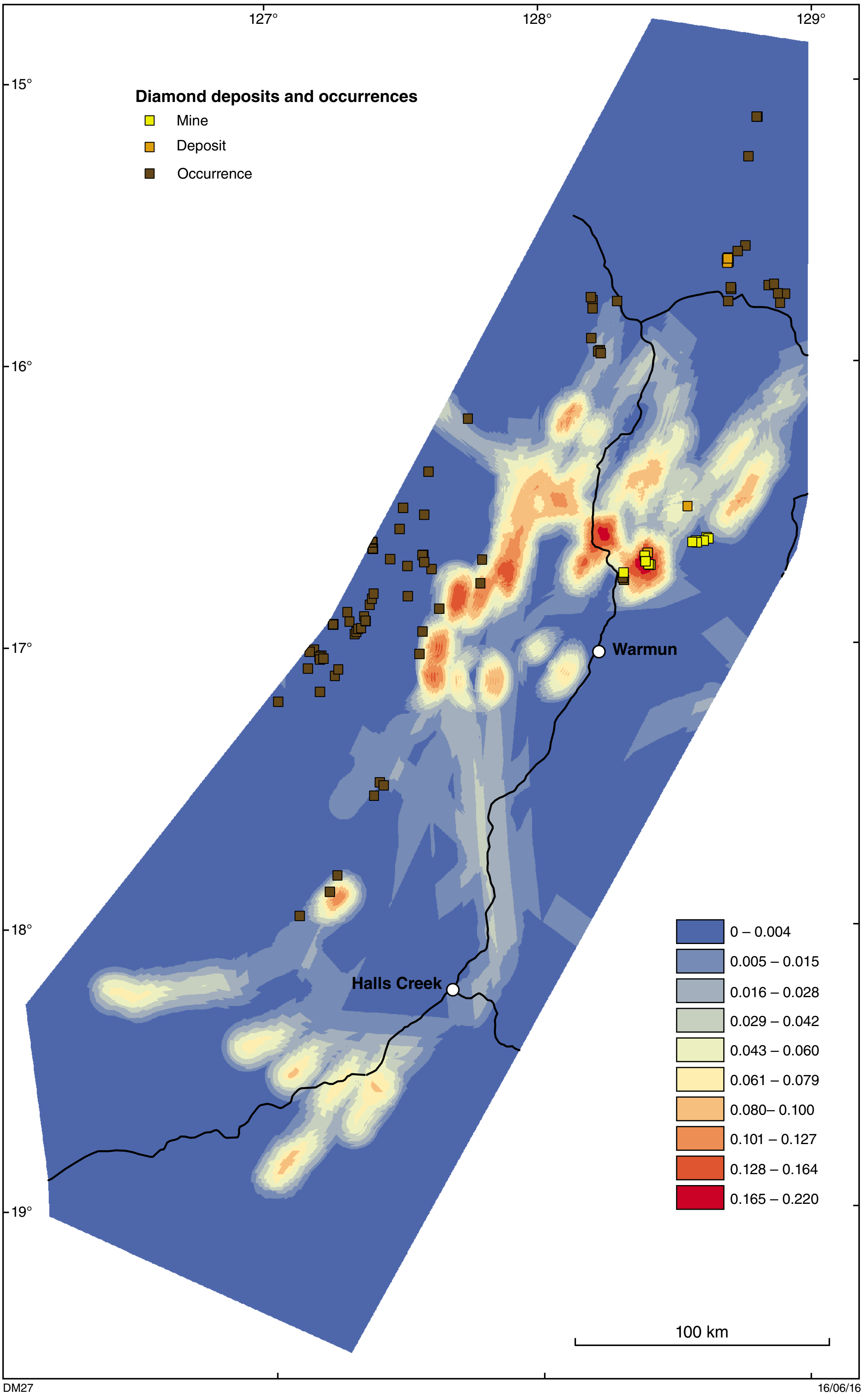


Figure 27. Prospectivity analysis for diamonds

Major crustal-scale faults or shear zones identified by Lindsay et al. (2016) are shown to control the location of known ore deposits. They are therefore implied to be sites of fluid migration and overlying or proximal sites of ore deposition. Of these, orogen-perpendicular (northwesterly trending) and orogen-oblique (northerly trending) faults seem to be the most influential structures with respect to ore deposition in the Halls Creek Orogen, especially where they intersect each other or orogen-parallel faults and shears.

In summary, the Eastern Zone appears to be the most prospective for Au-only mineralization, whereas the Central Zone is most prospective for Cu–Au–Mo and Pb–Zn–Cu–Ag mineralization. Regional-scale prospectivity analysis for REE was difficult to complete, mainly due to the resolution of the data used for the analysis and the relatively small size expected for a REE deposit. In situ diamond prospectivity might be restricted to the Central and Western Zones. The Central Zone was also found to be prospective for Ni–Cu–PGE–V–Ti, as were parts of the Western Zone which, along with the Eastern Zone, may be prospective for Sn, W (and Mo) mineralization.

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Appendix

GIS-based mineral prospectivity analysis of the Halls Creek Orogen, Western Australia: user guide

Introduction

This user guide is an accompaniment to the GIS-based mineral prospectivity analysis of this Report. This guide should therefore be read in conjunction with this Report, which documents the methodology and interpretation of a knowledge-driven, fuzzy-logic approach to prospectivity modelling of the Halls Creek Orogen.

Project background

The Proterozoic Halls Creek Orogen hosts a variety of mineralization styles and deposit types. At the time of writing, operating mines in the area included Ridges Iron Ore, Savannah (Ni and PGE), and Argyle (diamonds). Historical mining includes Au in the Eastern Zone of the Halls Creek Group, and Pb, Cu, Ag, Au, and Sb in the Central and Western Zones of the orogen.

The GIS-based mineral prospectivity study of this Report examined several mineral deposit types to determine the differences and similarities of their global- to large-scale conceptual features. These features were used to apply an automated to semi-automated approach to mineral systems analysis and prospectivity analysis (targeting) of the Halls Creek Orogen at a regional- to district-scale. Seven prospectivity models were generated for diamonds: PGE, NiS, Cu, Au, Zn, Pb, light and heavy REE, rare metals, and Au.

The mineral systems approach was based on assessing the five main geological elements required to form, focus, deposit, and preserve a mineral deposit (Fig. 1). They are:

- deep crustal-scale features (lithospheric architecture)
- tectonic triggers (geodynamic throttle)
- fertility elements (e.g. metal source, fluid compositions, oxidation state)
- depositional site (structure, rock types)
- preservation (within crust).

Project conclusions

Based on the prospectivity analysis, the Eastern Zone of the Halls Creek Orogen appears to be most prospective for Au-only mineralization, whereas the Central Zone is possibly most prospective for Cu–Au–Mo and Pb–Zn–Cu–Ag mineralization. Regional-scale prospectivity analysis for REE was problematic due to low data resolution used for the analysis and the relatively small size expected for a REE deposit. In situ diamond prospectivity appears to be restricted to the Central and Western Zones and Cu–Au–Mo mainly in the Central Zone. The Central Zone was also found to be prospective for Ni–Cu–PGE–V–Ti, as were parts of the western zone, which along with the Eastern Zone may be prospective for Sn, W (and Mo) mineralization.

Generating GIS prospectivity maps

Seven prospectivity models can be run to generate the prospectivity maps using the ArcGIS ‘HCO prospectivity’ tool. They are:

- Au only
- diamonds
- Ni–Cu–PGE–V–Ti
- REE
- Cu–Au–Mo

- Pb–Zn–Cu–Ag
- Sn–W–(Mo).

A default set of confidence levels or evidence weights has been assigned to selected geological features (Fig. 1) for the models. However, these values can be changed by the user to better reflect their understanding of critical inputs to prospectivity analysis.

Software requirements

- Windows 7 or 8
- ArcGIS 10.2 with 'Spatial Analyst' extension
- Media player for running WMV video files in this user guide. Files can be accessed on the website at <www.dmp.wa.gov.au/ebookshop>.

Getting started

Key points

- Ensure 'Spatial Analyst' is turned on (found under Customize/Extensions)
- Click on 'HCO prospectivity' in ArcToolbox to begin prospectivity modelling.

Building your own prospectivity map

This video looks at the prospectivity of diamonds to illustrate how to change confidence factors and evidence weights to suit your requirements and how to run and save your model.

Key points

- Ensure 'Spatial Analyst' is turned on (found under Customize/Extensions)
- 'Confidence factors' or 'evidence weights' can be chosen from 0 to 1.0, in 0.1 increments only
- Your output file must be renamed, as the original model file name cannot be overwritten
- Model run-time varies from less than 1 minute to several minutes depending on model complexity (Au only being the most complex and diamonds the least complex).

Changing the appearance of your prospectivity map

This video shows you how to change the colour ramp of your prospectivity map and the number of data subdivisions you want to display.

FAQ

1. My model will not run.

Ensure you have renamed the output file, as the original model file name cannot be overwritten (see HCO Video 1.wmv).

2. The 'HCO prospectivity' tool won't open the prospectivity model group.

Ensure 'Spatial Analyst' is turned on (found under Customize/Extensions; see HCO Video 1.wmv).

3. My map is mostly black.

There may be too many confidence factors or evidence weights assigned to 0. Change some to greater than 0 (see HCO Video 2.wmv).

A multicommodity mineral systems analysis has been carried out as the basis for prospectivity analyses and mapping in the greenfields Halls Creek Orogen in northern Western Australia. Known mineral occurrences or deposits in the region formed from 1860 Ma to 350 Ma, largely influenced by periods of supercontinent assembly and breakup, interspersed with periods of relaxation accompanied by extension and basin formation. A link was found between key mineral systems and prospectivity model components and the distribution of disparate styles of mineral deposits. Different terranes of the Halls Creek Orogen are prospective for diverse commodity groups due to the tectonic environment in which they developed, their potential to be preserved at the present-day surface or subsurface, and the presence of favourable depositional sites (structural or lithological). Major crustal-scale faults or shear zones that control the location of known ore deposits are implied to be sites of fluid migration and proximal to sites of ore deposition. Of these, orogen-perpendicular (northwesterly trending) and orogen-oblique (northerly trending) faults seem to be the most influential structures, especially in regions where they intersect each other or orogen-parallel (northeasterly trending) major crustal-scale structures.

Further details of geological products and maps produced by the Geological Survey of Western Australia are available from:

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