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Focus Paper

The tectonics and mineral systems of Proterozoic Western Australia: Relationships with supercontinents and global secular change

A.R.A. Aitken [a,*], S.A. Occhipinti [a], M.D. Lindsay [a], A. Joly [a,1], H.M. Howard [b], S.P. Johnson [b], J.A. Hollis [b,2], C.V. Spaggiari [b], I.M. Tyler [b], T.C. McCuaig [a,c,d], M.C. Dentith [a]

[a] Centre for Exploration Targeting, The University of Western Australia, Perth, Western Australia, Australia
[b] The Geological Survey of Western Australia, Department of Mines and Petroleum, Perth, Western Australia, Australia
[c] BHP Billiton, 125 St Georges Terrace, Perth, Australia
[d] ARC Centre of Excellence for Core to Crust Fluid Systems, Centre for Exploration Targeting, School of Earth Sciences, The University of Western Australia, Australia

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ABSTRACT

The cratonisation of Western Australia during the Proterozoic overlapped with several key events in the evolution of Earth. These include global oxidation events and glaciations, as well as the assembly, accretionary growth, and breakup of the supercontinents Columbia and Rodinia, culminating in the assembly of Gondwana. Globally, Proterozoic mineral systems evolved in response to the coupled evolution of the atmosphere, hydrosphere, biosphere and lithosphere. Consequently, mineral deposits form preferentially in certain times, but they also require a favourable tectonic setting. For Western Australia a distinct plate-margin mineralisation trend is associated with Columbia, whereas an intraplate mineralisation trend is associated with Rodinia and Gondwana, each with associated deposit types. We compare the current Proterozoic record of ore deposits in Western Australia to the estimated likelihood of ore-deposit formation. Overall likelihood is estimated with a simple matrix-based approach that considers two components: The "global secular likelihood" and the "tectonic setting likelihood". This comparative study shows that at least for the studied ore-deposit types, deposits within Western Australia developed at times, and in tectonic settings compatible with global databases. Nevertheless, several deposit types are either absent or poorly-represented relative to the overall likelihood models. Insufficient exploration may partly explain this, but a genuine lack of deposits is also suggested for some deposit types. This may relate either to systemic inadequacies that inhibited ore-deposit formation, or to poor preservation. The systematic understanding on the record of Western Australia helps to understand mineralisation processes within Western Australia and its past connections in Columbia, Rodinia and Gondwana and aids to identify regions of high exploration potential.

1. Introduction

Western Australia (WA) possesses several Archean nuclei, as well as the orogenic belts through which Precambrian Australia was assembled (Fig. 1). Tectonic events within WA strongly reflect the evolution of the Proterozoic supercontinents Columbia (or Nuna), Rodinia and Gondwana (e.g. Betts and Giles, 2006; Cawood and Korsch, 2008; Aitken et al., 2016). The observed tectonic processes include mineralisation events, which respond not only to tectonic influences, but also to secular-change in the atmosphere, hydrosphere, biosphere and the solid-earth (Groves et al., 2005b; Goldfarb et al., 2010; Cawood and Hawkesworth, 2014; McCuaig and Hronsky, 2014).

WA has a wide variety of mineral deposits, many of which are world class. The best known mineral systems include Archean orogenic gold (Blewett et al., 2010), komatiite-associated nickel (Barnes and Fiorentini, 2012) and iron-ore deposits in the Archean–Proterozoic Hamersley Basin (Taylor et al., 2001). The

* Corresponding author.
E-mail address: alan.aitken@uwa.edu.au (A.R.A. Aitken).
Peer-review under responsibility of China University of Geosciences (Beijing).
[1] Now at Resource Potentials, Perth, Australia.
[2] Now at Department of Geology, The Ministry of Mineral Resources, Greenland Government, Greenland.

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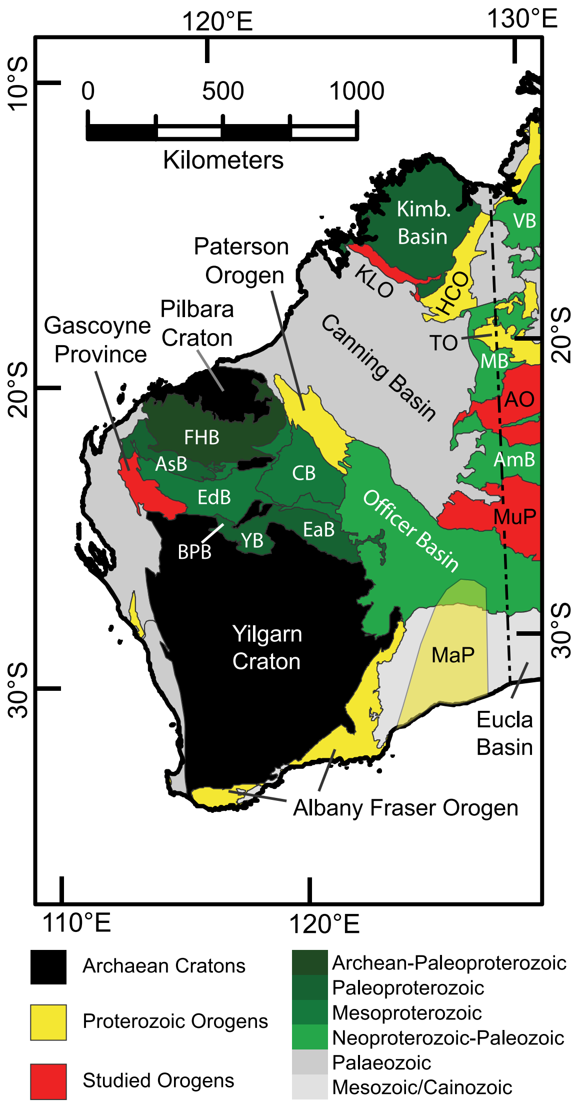

Figure 1. Map of western Australia showing Proterozoic-dominated metamorphic/magmatic belts in yellow, with focus regions highlighted in red. These include the King Leopold (KLO), Halls Creek (HCO), Tanami (TO), Arunta (AO), Albany-Fraser and Paterson orogens, as well as the Gascoyne, Musgrave (MuP), and Madura (MaP) provinces. Basins include the Archean–Paleoproterozoic Fortescue-Hamersley Basin (FHB), the Paleoproterozoic Kimberley Basin and the Paleoproterozoic to Mesoproterozoic basins of the Capricorn Orogen, including the Earaheedy (EaB), Yerrida (YB) and Bryah-Padbury (BPB) basins in the south, the Ashburton Basin (AsB) in the north and the Edmund (EdB) and Collier (CB) basins in the centre. Components of the Neoproterozoic to Paleozoic Centralian Superbasin are in lighter green – the Officer, Amadeus (AmB) Murraba (MB) and Victoria (VB) Basins. The last two are underlain by Paleoproterozoic Birrindudu Basin.

mineral systems for most Proterozoic ore-deposits are less well-known, with several cases defined by a single major deposit (e.g. Telfer (Goellnicht et al., 1991; Rowins et al., 1997; Maidment et al., 2010), Abra (Vogt and Stumpfl, 1987)). A better understanding of the context of these mineral systems will aid better understand resource potential within WA and the regions once connected within Columbia, Rodinia and Gondwana.

In this review, we summarise the Proterozoic tectonic evolution of Western Australia, and undertake a high-level analysis to establish how variations in tectonic setting and global secular change have combined to influence the likelihood of ore-deposit formation. The key question is to what degree the observed Proterozoic mineral deposits of Western Australia are consistent with, firstly, global empirical databases of resource endowment though time, and secondly, the influence of tectonic setting on ore deposit formation.

We show that the type and abundance of major Proterozoic ore-deposits found within Western Australia can largely be understood through the nature of tectonic events operating in the region, and their timing with respect to global secular change. Nonetheless, certain ore-deposit types are under-represented, and for these we put forward possible reasons for the apparent lack of deposits.

2. Global secular change in mineralisation

Economically viable ore deposits are very rare occurrences in the geological record, and form only under certain tectonic and atmospheric conditions (McCuaig and Hronsky, 2014). Empirical studies of the abundance of endowment within major ore deposit types through time, and correlations with other proxies for the evolution of the Earth, allow for the definition of some of the large-scale and long-term influences on the likelihood of ore-deposit formation (Groves et al., 2005b). Such studies have been conducted for deposit types including orogenic gold (Groves et al., 2005a), sediment hosted base metals (SHBMs) (Hitzman et al., 2010; Leach et al., 2010), Volcanic hosted massive sulphide (VHMS) (Huston et al., 2010), iron formations (Bekker et al., 2010), IOCGs (Groves et al., 2010) and magmatic nickel, copper and platinum group elements (Ni-Cu-PGE) (Naldrett, 2010).

2.1. Orogenic gold deposits

For orogenic gold, an extensive deposit database is available and this highlights the predominance of several key periods (Fig. 2). The highest abundances are found during the periods of 2.2–1.8 Ga and 0.7–0.4 Ga, which coincides with the assembly of the supercontinents Columbia and Gondwana. This suggests a strong link with convergent margin processes, and in particular, the formation of new crust through juvenile magmatism (Cawood and Hawkesworth, 2014). The assembly of Rodinia however has no similar peak, which, in line with other evidence, suggests that the transition from Columbia to Rodinia was largely associated with the recycling and reorganisation of existing crustal elements (Cawood and Hawkesworth, 2014).

2.2. Sedimentary-hosted base metal deposits

SHBM deposits occur in three dominant styles, clastic-dominated (CD) lead-zinc, Mississippi Valley Type lead-zinc (MVT) and sedimentary-hosted copper. Leach et al. (2010) summarised the first two through Earth's history: CD-SHBM deposits occur after the Paleoproterozoic Great Oxidation Event (GOE), and metal abundance is concentrated in several key periods, from 1.85 Ga to 1.4 Ga, ca. 1.2 Ga, ca. 0.7 Ga and 0.6 to 0.1 Ga (Fig. 2). MVTs remain very rare until a second GOE in the late Neoproterozoic, and most occur after ca. 450 Ma (Leach et al., 2010). GOEs permit the large scale mobilization of lead and zinc into the hydrosphere and allow for oxidised brines, and sulphate bearing evaporates to exist. For MVTs the development of highly permeable carbonates in the Paleozoic is also of key importance (Leach et al., 2010). A final control on the abundance of these deposits is the formation and preservation of large-scale intracontinental basins and passive margins, most notably following the assembly of Columbia and Gondwana (Leach et al., 2010).

Sedimentary-hosted copper deposits are also restricted to after the GOE, but have dominantly formed at different times to lead-zinc deposits (Hitzman et al., 2010). Metal abundance is most prominent in the second half of the Neoproterozoic (Fig. 2), largely associated with the central African Copper Belt, and again in the

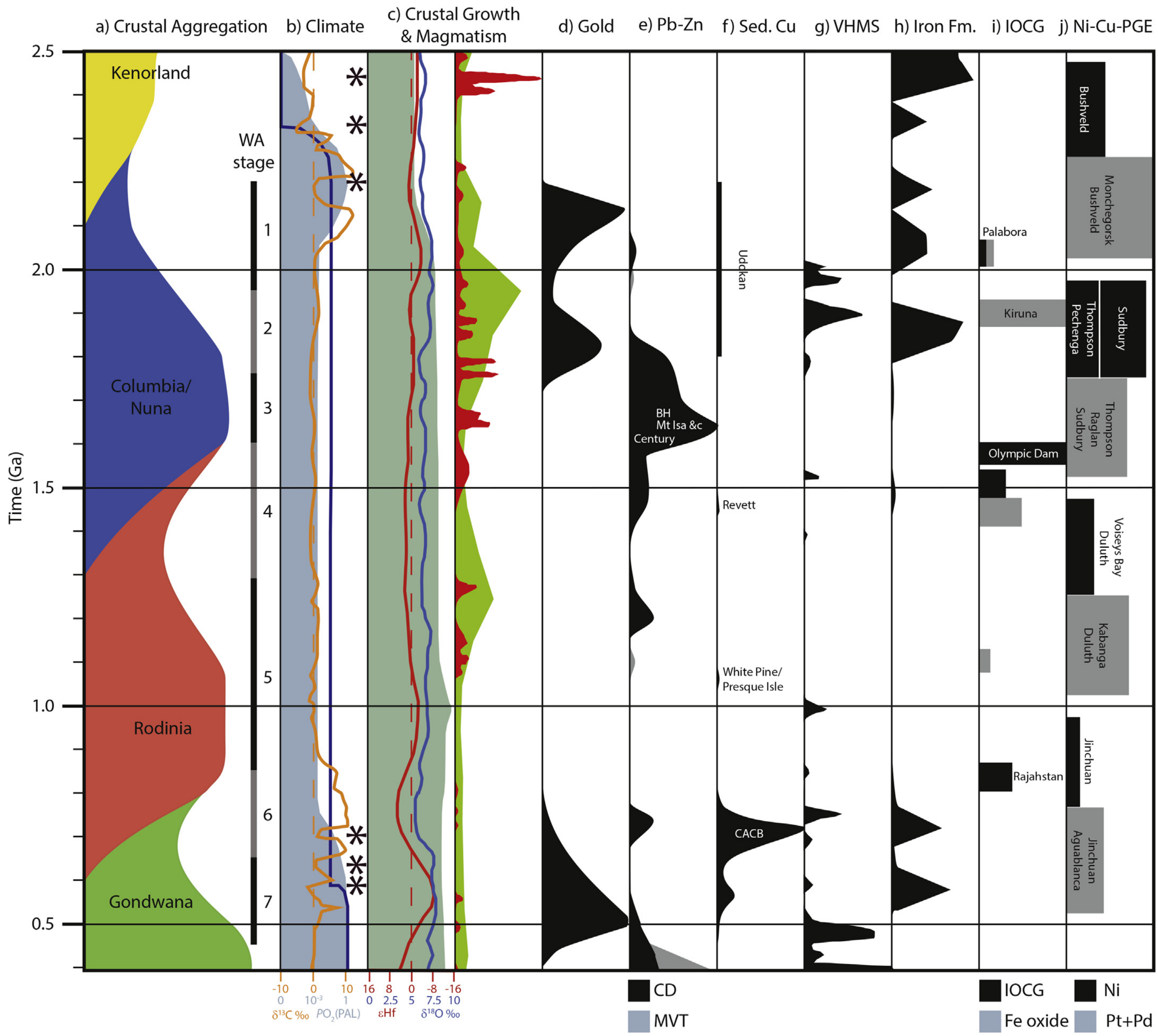

Figure 2. Global influences on ore-deposit formation, and the relative endowment from empirical databases. Plots show, (a) interpreted degree of crustal aggregation for each supercontinent, and the tectonic stages of Western Australia; (b) global climate influences, including atmospheric oxygen content from a newer (shaded) and a more traditional model (blue line) (both after Lyons et al., 2014), as well as $\delta^{13}C$ variations (Young, 2013). Positive $\delta^{13}C$ excursions indicate greater sequestration of ^{12}C from the oceans through organic processes. Snowflakes indicate major low-latitude glaciations (Young, 2013). (c) Crustal growth indicators showing interpreted relative crustal growth (shaded), median zircon ε_{Hf} (reversed) and $\delta^{18}O$ (Van Kranendonk and Kirkland, 2016). Lower $\delta^{18}O$ and higher ε_{Hf} are proxies for greater overall mantle input into magmatic rocks. Magmatism indicators include zircon frequency within interpreted juvenile crust (green) (Condie, 1998) and the abundance of mafic magmatism (red) (Abbott and Isley, 2002). (d) Relative abundance of orogenic Au (Goldfarb et al., 2010), (e) relative abundance of Pb + Zn in CD and MVT SHBMs (Leach et al., 2010), (f) relative abundance of Cu in sedimentary deposits (Hitzman et al., 2010), (g) relative abundance of 'ore' in VHMS deposits (Huston et al., 2010), (h) relative abundance of Fe in iron formations (Bekker et al., 2010), (i) endowments of major IOCG (Cu) and iron-oxide deposits (Fe) (Groves et al., 2010), (j) relative abundance of Ni and Pt-Pd for the major deposits within 500 Ma time bands (Naldrett, 2010). BH – Broken Hill, CACB – Central African Copper Belt.

Permian. This suggests a link with the early stages of the breakup of Rodinia and Pangaea, and the formation of intracontinental basins within which highly saline oxidised brines were able to circulate (Hitzman et al., 2010). A link is also suggested with large-scale glaciation events (Fig. 2), due to the formation of magnesium and sulphate rich oceans (Hitzman et al., 2010).

2.3. Iron formations

Overall, the presence of large scale iron formations is associated with anoxic ocean conditions and periods of intense mafic magmatism (Bekker et al., 2010). Therefore, in contrast to SHBMs, iron formations are preferentially found prior to ca. 1.85 Ga (Fig. 2). Iron formations can be texturally subdivided into banded iron formations (BIFs) and granular iron formations (GIFs) types, the latter forming in a shallower depositional environment. BIFs are predominant in the Archean and earliest Paleoproterozoic, with the largest concentration of deposits between 2.6 Ga and 2.4 Ga associated with a period of intense mafic magmatism (Bekker et al., 2010). After the GOE, GIFs became predominant, with the largest concentration deposited from ~1.93 Ga to 1.85 Ga, again associated with a period of intense mafic magmatism (Bekker et al., 2010). A

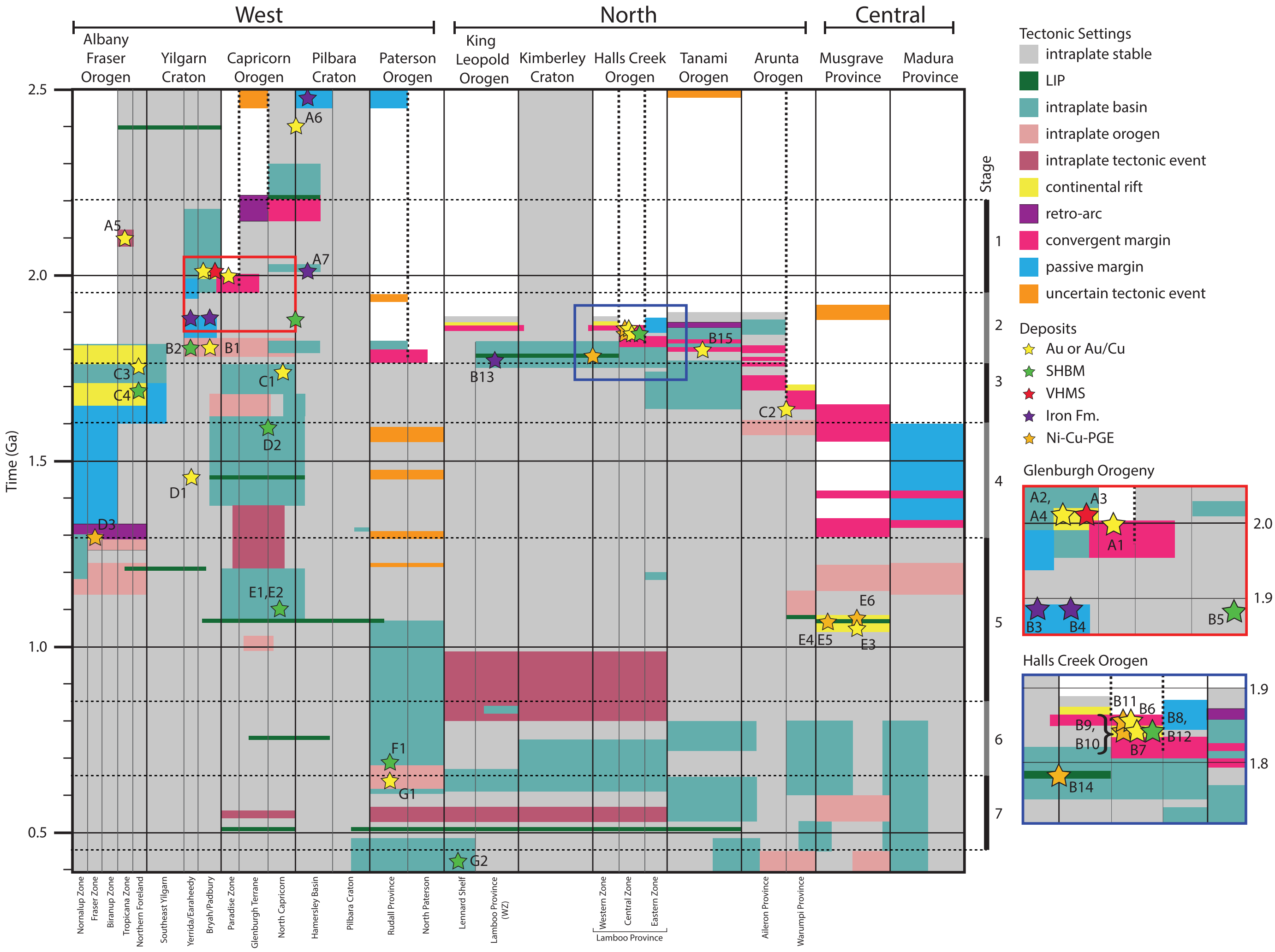

Figure 3. Time-space plot summarising the Proterozoic tectonics of Western Australia. Colours indicate different tectonic settings interpreted from a variety of literature sources (see text). Coloured star symbols indicate mineral deposits, as listed in Appendix B. West and North indicate the cratonic affinity of each region under the WAC-NAC-SAC schema of Myers et al. (1996). The Musgrave and Madura Provinces are distinct from the three major cratons, and these grouped into a Central Australian terrane. "Intraplate tectonic event" denotes a significant episode of deformation and reworking, but without widespread magmatism or pervasive high grade metamorphism (cf. intraplate orogeny).

prolonged period of absence follows, before a re-emergence temporally and spatially associated with Cryogenian glaciations (Fig. 2) and submarine volcanic deposits (Bekker et al., 2010).

2.4. *Volcanic-hosted massive sulphide deposits*

VHMS deposits form at the seafloor where upwelling hydrothermal fluids mix with seawater, and they form preferentially in back-arc basins, mid-ocean ridges and submarine volcanic arcs (Huston et al., 2010). These deposits occur in relative abundance throughout Earth history, although their tendency to form is influenced by several secular influences (Huston et al., 2010).

The distribution through time of these deposits (Fig. 2) shows distinct peaks at ca. 2.0–1.8 Ga, and 0.5–0.45 and 0.39–0.35 Ga, with lesser peaks at 0.75 Ga, 1.0 Ga and 1.5 Ga. These peaks suggest a link with the growth phases of Columbia, Gondwana and Pangaea. This relationship is likely associated with the predominance of retreating-slab conditions and the relative abundance of favourable back-arc basin settings (Huston et al., 2010). VHMS deposits are much less common during periods of low igneous activity, e.g. 2.5–2.2 Ga, 1.6–1.2 Ga and 1.0–0.75 Ga (Huston et al., 2010).

2.5. *Iron oxide copper gold deposits*

IOCGs are a relatively uncommon and quite poorly understood category of ore deposits, but nevertheless some key controlling factors are evident. IOCGs are strongly associated with intense alkaline magmatism events associated with melting of previously metasomatised lithospheric mantle (Groves et al., 2010). Major deposits are all located close to the margins of Archean cratons (Groves et al., 2010). Current data suggests that the major temporal peaks in (Fig. 2) are associated with individual mineral provinces, including the Palabora (ca. 2.05 Ga) and Olympic (ca. 1.59 Ga) IOCG provinces (Groves et al., 2010). Data are sparse and biased towards the largest deposits, but they indicate that IOCGs may be most abundant in the Neoarchean, mid Paleoproterozoic and early Mesoproterozoic. Few examples are preserved from the late Mesoproterozoic, Neoproterozoic and Phanerozoic. Consequently, links are suggested with, firstly, the presence of established continents comprising Archean cratons, secondly, a link with magmatic trends, and thirdly a strong link with the Columbia supercontinent, with much lower abundance in later supercontinents (Groves et al., 2010).

2.6. Ni-Cu-PGE

Proterozoic magmatic nickel, copper and PGE deposits form in close association with mafic magmatic events associated with rifting, mantle plume events and, in one key case, bolide impact (Naldrett, 2010). Broadly, they can be separated into the relatively sulphide-rich nickel dominated deposits, and relatively sulphide-poor PGE-dominated deposits, each of which has different controls on the formation of economic metal concentrations (Naldrett, 2010).

As with IOCG deposits, the record of Ni-Cu-PGE endowment through time is dominated by a few major provinces. Excluding the impact-related Sudbury deposit, nickel endowment appears to decline through the Proterozoic (Naldrett, 2010). Platinum and palladium endowment also declines, but with a less regular pattern (Naldrett, 2010).

3. A summary of Proterozoic Western Australia

Western Australia comprises several Archean cratons which were amalgamated in a multi-stage process involving several Proterozoic orogens (Myers et al., 1996; Cawood and Tyler, 2004; Cawood and Korsch, 2008; Aitken et al., 2016). In this section we will briefly review the tectonics of these orogens and relevant parts of the adjacent cratons.

The tectonics and mineral systems of several of these regions have recently been analysed in detail, including numerical mineral systems analysis (Fig. 1). We focus on the Gascoyne Province (Aitken et al., 2014; Joly et al., 2015), the King Leopold Orogen (Lindsay et al., 2015a,b), the west Arunta Orogen (Joly et al., 2013, 2015) and the west Musgrave Province (Joly et al., 2014, 2015). The western Tanami Orogen (Joly et al., 2010, 2012) and the Halls Creek Orogen have also been analysed using similar methods (Occhipinti et al., 2016).

3.1. The Capricorn Orogen

The Capricorn Orogen is located between the Archean Pilbara and Yilgarn Cratons (Fig. 1), also incorporating the isotopically distinct Glenburgh Terrane. The Pilbara Craton and the Glenburgh Terrane were amalgamated during the ca. 2215 Ma to 2145 Ma Opthalmia Orogeny, for which the Lyons-River Fault (Fig. 4) is interpreted to be the primary suture (Johnson et al., 2013). The southern Pilbara Craton and the ca. 2775–2630 Ma Fortescue and

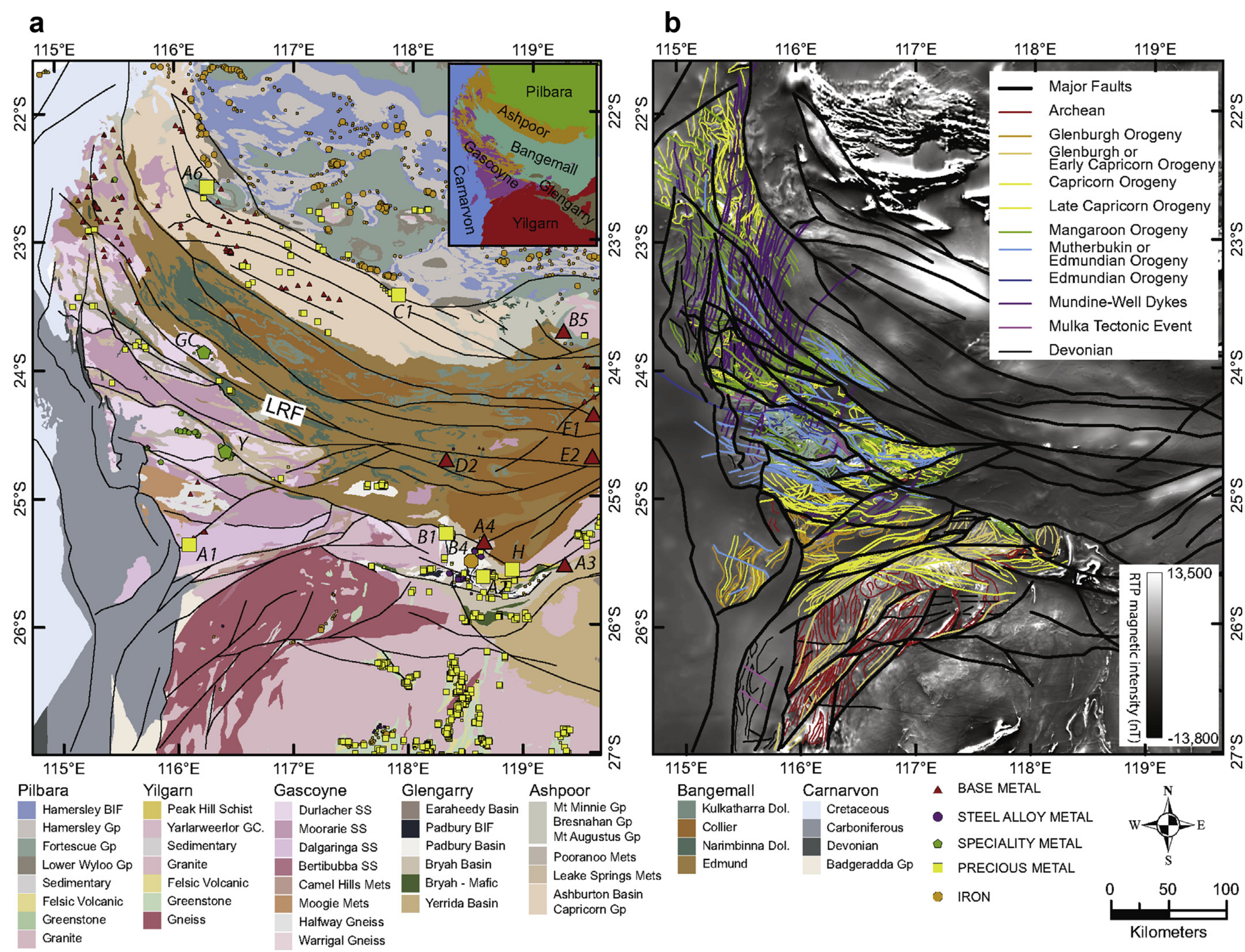

Figure 4. The western Capricorn Orogen, showing (a) geology and mineral deposits/occurences; deposits are named as in Appendix B apart from the REE deposits at Gifford Creek (GC) and Yinnietharra (Y), gold at Hermes (H) and the widespread Hamersley Basin iron deposits. LRF designates the Lyons River Fault. (b) The structural interpretation of Aitken et al. (2014), showing the ages of structures (last motions).

ca. 2630–2445 Ma Hamersley basins were deformed significantly during this event.

The ca. 2005 Ma to 1955 Ma Glenburgh Orogeny affected the southern Capricorn Orogen and involved north-dipping subduction, forming a continental arc (Dalgaringa Supersuite), followed by collision of the previously combined Glenburgh/Pilbara Craton block with the Yilgarn Craton (Occhipinti et al., 2004; Sheppard et al., 2004; Johnson et al., 2011). At the same time, the northern Yilgarn Craton experienced a prolonged period of subsidence and rifting in the Yerrida, Earaheedy, Bryah and Padbury basins (Sheppard et al., 2016). These basins continued to subside up until the ca. 1.8 Ga Capricorn Orogeny.

Following the plate-margin events, the Capricorn Orogen experienced episodic reactivation in an intraplate setting, including at least five major tectonic events, two intraplate basin forming events, and three mafic sill/dyke swarms (Fig. 3). The intraplate 1820–1780 Ma Capricorn Orogeny is responsible for much of the current tectonic architecture of the region, including the voluminous and widely distributed Moorarie Supersuite granitoids. Sedimentation and defomation is recorded in the Ashburton Basin during this event (Johnson et al., 2013).

After a ~100 Ma tectonic hiatus, the Capricorn Orogen was again affected by an intraplate tectonic event, the ca. 1680–1620 Ma Mangaroon Orogeny (Sheppard et al., 2005). The 1680–1650 Ma Durlacher Supersuite (Sheppard et al., 2005) granites were intruded, partially into the metasedimentary Pooranoo Metamorphics (Sheppard et al., 2005). This event was less widespread than the Capricorn Orogeny, with activity being focused towards the north-west of the orogen (Fig. 4b).

Following the Mangaroon Orogeny, sedimentary rocks of the 1679 to 1455 Ma Edmund Group were deposited in a basin that once covered much of the orogen (Cutten et al., 2016). This basin was intruded by sills of the mafic Narimbunna Dolerite at ca. 1465 Ma (Sheppard et al., 2010). Further deformation and metamorphism – the Mutherbukin Tectonic Event - affected the orogen between 1321 Ma and 1171 Ma (Sheppard et al., 2010). The ca. 1171–1067 Ma Collier Group is poorly preserved in the western Capricorn Orogen, but it is extensive in the east (Cutten et al., 2016) (Fig. 1). Peperitic textures associated with sills of the ca. 1070 Ma Kulkatharra Dolerite suggest that the Collier Group was deposited shortly prior to intrusion (Cutten et al., 2016).

The Edmundian Orogeny occurred between 1026 Ma and 954 Ma and involved folding and low-grade metamorphism of the Edmund and Collier Groups, as well as the intrusion of the Thirty Three Supersuite granites and rare-earth-element (REE) bearing pegmatites, e.g. Yinniethara (Sheppard et al., 2007, 2010). Magatism was focused within a narrow and centrally located region (Fig. 4). The north-northeast trending Mundine Well Dyke Swarm intruded into the northwestern Capricorn Orogen at ca. 755 Ma (Wingate and Giddings, 2000). The ca. 570 Ma Mulka Tectonic event is characterised by dextral shear zones focused around the major crustal boundaries, with significant cumulative offsets, e.g. ~35 km at the Chalba Shear Zone (Sheppard et al., 2010).

3.1.1. Observed mineralisation

Proterozoic ore deposits in the Capricorn Orogen include orogenic gold (Paulsens (A6), Glenburgh (A1), Harmony-Peak Hill (A2)) and structurally-controlled gold dating to the Capricorn Orogeny (Mt Olympus (C1), Labouchere-Fortnum and Nathans (B1)). VHMS deposits are found in the Bryah Basin (DeGrussa (A3), Horseshoe Lights (A4)). Base metals are found in the Edmund Group (Abra (D2)), shear-hosted zinc-lead (Prairie Downs (B5)) and copper (Ilgarari (E1), Kumarina (E2)), lead-in-carbonate (Magellan (B2)) and epithermal copper-silver (Thaduna (D1)). Iron formations are found in the Hamersley, Padbury (B4) and Earaheedy (B3) basins, although only the first contains currently economic deposits. Carbonatite and pegmatite hosted REE deposits are found in the Gascoyne Province (Gifford Creek and Yinnietharra deposits). Mineral prospectivity analyses for the Gascoyne Province are available from Aitken et al. (2014) and Joly et al. (2015).

3.2. The Paterson Orogen

The Paterson Orogen describes the region that separates the West Australian Craton and North-Australian Craton (Bagas, 2004). The Paterson Orogen is largely overlain by the Early Ordovician to Early Cretaceous Canning Basin (Fig. 1). Proterozoic rocks are exposed in the south, where Neoproterozoic Yeneena Basin overlies a largely Mesoproterozoic basement. Isotopic studies suggest that this basement was derived from the West Australian Craton (Kirkland et al., 2013), and may represent a Paleoproterozoic passive margin.

The basement was comprehensively reworked during the 1800–1765 Ma Ga Yapungku Orogeny, which involved felsic magmatism, high-pressure amphibolite-granulite facies metamorphism, and ENE–WSW oriented thrust stacking (Smithies and Bagas, 1997). This orogeny is commonly interpreted to represent collision of the West Australian Craton with the North Australian Craton (Myers et al., 1996; Smithies and Bagas, 1997; Betts et al., 2002). Although no suture is exposed, this is supposed to exist further north within the Paterson Orogen. Subsequent magmatic events occurred at ca. 1590–1550 Ma, ca. 1475–1450 Ma, ca. 1310–1290 Ma and ca. 1222 Ma (Bagas, 2004; Kirkland et al., 2013).

The Yeneena Basin includes the Tarcunyah, Throssell Range and Lamil groups, deposited after ca. 1070 Ma but before the 680–610 Ma Miles Orogeny (Bagas, 2004). The Miles Orogeny involves northwest trending folds and thrust faults (Bagas, 2004), exhumation (Durocher et al., 2003), and several phases of felsic magmatism between 678 Ma (Bagas, 2004) and 615 Ma (Wyborn, 2001). The glacigene Boondawari Formation, correlated to the Elatina formation, provides a minimum bound for the Miles Orogeny of ca. 610 Ma (Bagas, 2004).

The Paterson Orogeny post-dates the Boondawari Formation and involved SSW–NNE shortening indicated by NNW and ENE oriented shear zones, and east to southeast trending open folding (Bagas, 2004). The age of the Paterson Orogeny is commonly inferred to be ca. 550 Ma, based on very limited $^{40}Ar/^{39}Ar$ geochronology (Durocher et al., 2003) and comparisons with the Petermann Orogeny.

3.2.1. Mineralisation

The major deposits in the Paterson Orogen include tungsten at O'Callaghans, uranium at Kintyre gold-copper at Telfer (G1) and stratigraphic copper at Nifty (F1). Nifty formed within the Throssell Range group (Anderson et al., 2001), and has been dated at 791 ± 43 Ma (Huston et al., 2005). The Telfer gold-copper mine is hosted within the Lamil Group in the structural culmination of Telfer Dome (Goellnicht et al., 1991; Rowins et al., 1997). Dating at Telfer suggests mineralisation occurred between 652 ± 7 Ma and 645 ± 7 Ma (Maidment et al., 2010).

3.3. The Kimberley Craton and its margins

The Paleoproterozoic Kimberley Basin overlies the granitic basement of the Kimberley Craton. It is flanked to the south and east by the Paleoproterozoic Lamboo Province, exposed within the King Leopold and Halls Creek orogens (Fig. 1). Geophysical, geochemical and geochronological evidence suggests that the Kimberley Craton is Archean (Fishwick et al., 2005; Hollis et al., 2014).

The Lamboo Province records the multi-stage incorporation of the Kimberley Craton into the North-Australian Craton during the ca. 1865–1850 Ma Hooper Orogeny and the ca. 1835–1805 Ma Halls Creek Orogeny (Griffin et al., 2000; Tyler et al., 2012; Lindsay et al., 2016).

The Hooper Orogeny is observed in the western and central zones of the Lamboo Province. The initial stages of the Hooper Orogeny involved rifting of the western zone, and the deposition of the ca. 1872 Ma Marboo Formation. At ca. 1855 Ma, the felsic volcanic and volcaniclastic rocks of the Whitewater Volcanics and the voluminous granitic and minor gabbroic intrusive rocks of the Paperbark Supersuite were emplaced (Bodorkos et al., 1999; Griffin et al., 2000; Sheppard et al., 2001). In the central zone, the sedimentary, volcanic and volcaniclastic rocks of the Tickalara Metamorphics were deposited from ca. 1865 Ma, before being intruded by the ca. 1850 Ma Dougalls Suite and the Panton Suite (1856 ± 2 Ma). Collectively, these rocks have been interpreted to represent an oceanic island arc above an east-dipping subduction zone later evolving into an accretionary orogen (Griffin et al., 2000; Sheppard et al., 2001; Tyler et al., 2012; Lindsay et al., 2016). Alternatively an ensialic marginal basin associated with a west-dipping subduction zone has been proposed (Griffin et al., 2000). Geodynamic numerical modelling has recently provided support for the latter (Kohanpour et al., 2017). Following the Hooper Orogeny, a relatively localised basin formed, containing the Koongie Park Formation, and the mafic intrusions of the Sally Malay Suite (1844 ± 3 Ma) were intruded, perhaps indicating rifting (Griffin et al., 2000; Lindsay et al., 2016).

The ca. 1835 Ma to 1805 Ma Halls Creek Orogeny records the accretion of the Kimberley Craton to the North Australian Craton (Blake et al., 2000; Tyler et al., 2012). The Sally Downs Supersuite was intruded, with geochemistry suggestive of formation in an arc-like environment (Sheppard et al., 2001). West-dipping subduction is suggested, leading to collision of the central and eastern zones and the formation of a coherent North Australian Craton (Sheppard et al., 2001).

Following the Halls Creek Orogeny, the Kimberley region experienced a sustained period of intraplate basin formation, likely as a result of post-orogenic relaxation (Hollis et al., 2014). The 1835–1805 Ma Speewah Basin formed around the fringes of the Kimberley Craton. From ca. 1805 Ma to 1790 Ma the lower Kimberley subgroup, comprising the King Leopold Sandstone and the predominantly basaltic Carson Volcanics, was then deposited over the Speewah Group. Both the Speewah Group and lower Kimberley subgroup were intruded by the mafic sills, dykes and granophyric intrusions of the ca. 1790 Ma Hart Dolerite. The upper Kimberley subgroup are younger, and may have formed between ca. 1790 Ma and 1740 Ma (Sheppard et al., 2012; Hollis et al., 2014) before being intruded by a second suite of dolerite sills and dykes.

Overall quiescence during the Mesoproterozoic and Neoproterozoic was interrupted by several low-intensity tectonic events. These include the poorly dated Yampi Orogeny (1–0.8 Ga), ca. 830 Ma basin formation, Cryogenian glaciations and the ca. 550 Ma King Leopold Orogeny (Tyler et al., 2012). None of these is associated with regional magmatism or pervasive metamorphism.

3.3.1. Mineralisation

Most deposits in the Kimberley region are in the Halls Creek Orogen. They include orthomagmatic nickel-copper-cobalt at Savannah (B9) and Copernicus (B10), dated ca. 1845 Ma; PGE-gold-nickel copper at Panton (B11), dated 1856 ± 2 Ma; vanadium, titanium and fluorite at Speewah (B14), dated 1797 ± 11 Ma; intrusion-related gold and silver dated ca. 1870–1850 Ma (B6), porphyry copper at Mt Angelo (B7), dated 1845–1840 Ma; VHMS at Koongie Park (B8), dated ca. 1845–1840 Ma; diamonds in lamproite pipes at Argyle, dated ca. 1180 Ma; SHBMs, with CD at Ilmars (B12), dated ca. 1875 Ma and Mississippi Valley Type (MVT) in Devonian and lower Carboniferous reef complexes. For more detailed analyses of these mineral systems see Occhipinti et al. (2016).

Deposits in the King Leopold Orogen (Fig. 5) are less abundant and less diverse but include a major MVT system in Devonian reef complexes on the Lennard Shelf (G2), diamonds in lamproites at Ellendale (ca. 20 Ma) and granular iron formation deposits at Koolan, Irvine and Cockatoo Islands (B13), dated ca. 1745 Ma. For more detailed analyses of these mineral systems see Lindsay et al. (2015a,b).

3.4. The Tanami Orogen

The Tanami Orogen sits within the North Australian Craton, between the Halls Creek Orogen and Arunta Orogen (Fig. 1). Over the last decade, several studies have been completed in the area, largely driven by the extensive gold mineralisation (Crispe et al., 2007; Joly et al., 2010, 2012; Stevenson et al., 2013; Bagas et al., 2014). Isolated inliers of the Neoarchean Billabong Complex (2514 ± 3 Ma; Page et al., 1995) and the undated Browns Range Metamorphics form the basement to the thick Paleoproterozoic successions of the Tanami Group (Joly et al., 2012).

The Tanami Group comprises the Dead Bullock and Killi-Killi formations. The Dead Bullock Formation is 2–3 km thick and is dominated by turbiditic sandstone, shale and chert, as well as mafic sills (Bagas et al., 2014). It was deposited at ca. 1865 Ma (Cross and Crispe, 2007; Li et al., 2013) in a probable back-arc basin environment (Bagas et al., 2008; Li et al., 2013). The Killi-Killi Formation is a 4–5 km thick sequence of siliciclastic rocks (Bagas et al., 2014) that formed between ca. 1865 Ma and ca. 1825 Ma (Claoué-Long et al., 2008). Seismic reflection imagery and gravity and magnetic modelling (Goleby et al., 2009; Joly et al., 2010) shows that the Tanami Group occupies a series of partially inverted half-grabens (Joly et al., 2010).

The Granites-Tanami Orogeny (GTO) occurred in several phases between ca. 1850 and ca. 1800 Ma (Joly et al., 2010; Stevenson et al., 2013; Bagas et al., 2014). The first phase (GTO-1) occurred after the deposition of the Killi-Killi Formation but prior to the intrusion of ca. 1800 Ma granitoids (Stevenson et al., 2013), and was perhaps related to the terminal collision of the Halls Creek Orogeny. GTO-2 is associated with granite intrusions and gold mineralisation, and has been interpreted as the main basin inversion event (Joly et al., 2010; Stevenson et al., 2013). A further event (GTO-3) has been interpreted by some authors, characterized by north-northeast-plunging open folds (Bagas et al., 2014).

Although not exposed, geophysical data suggest that a lithospheric-scale boundary, the Willowra Lineament, lies to the south of the Tanami Orogen, separating it from the Arunta Orogen (Goleby et al., 2009; Betts et al., 2016). This structure is considered the southern boundary of coherent North Australian lithosphere, and has been interpreted as a major Paleoproterozoic suture zone (Betts et al., 2016). It is not known when the collision occurred. An early-closure interpretation considers the Killi-Killi Formation and the Lander Rock Formation of the Aileron Province as stratigraphic equivalents (Claoué-Long et al., 2008; Goleby et al., 2009). This implies that collision occurred before ca. 1840 Ma, and consequently that the Tanami Orogeny was intraplate.

An alternative late-closure interpretation suggests collision occurred at ca. 1800 Ma, explaining the Tanami Orogeny and its gold mineral system (Bagas et al., 2010). Assuming that the similar detrital zircon provenance of the Killi-Killi Formation and the Lander Rock Formation (Claoué-Long et al., 2008) is not mere coincidence, collision at ca. 1800 Ma requires either a >25 Ma

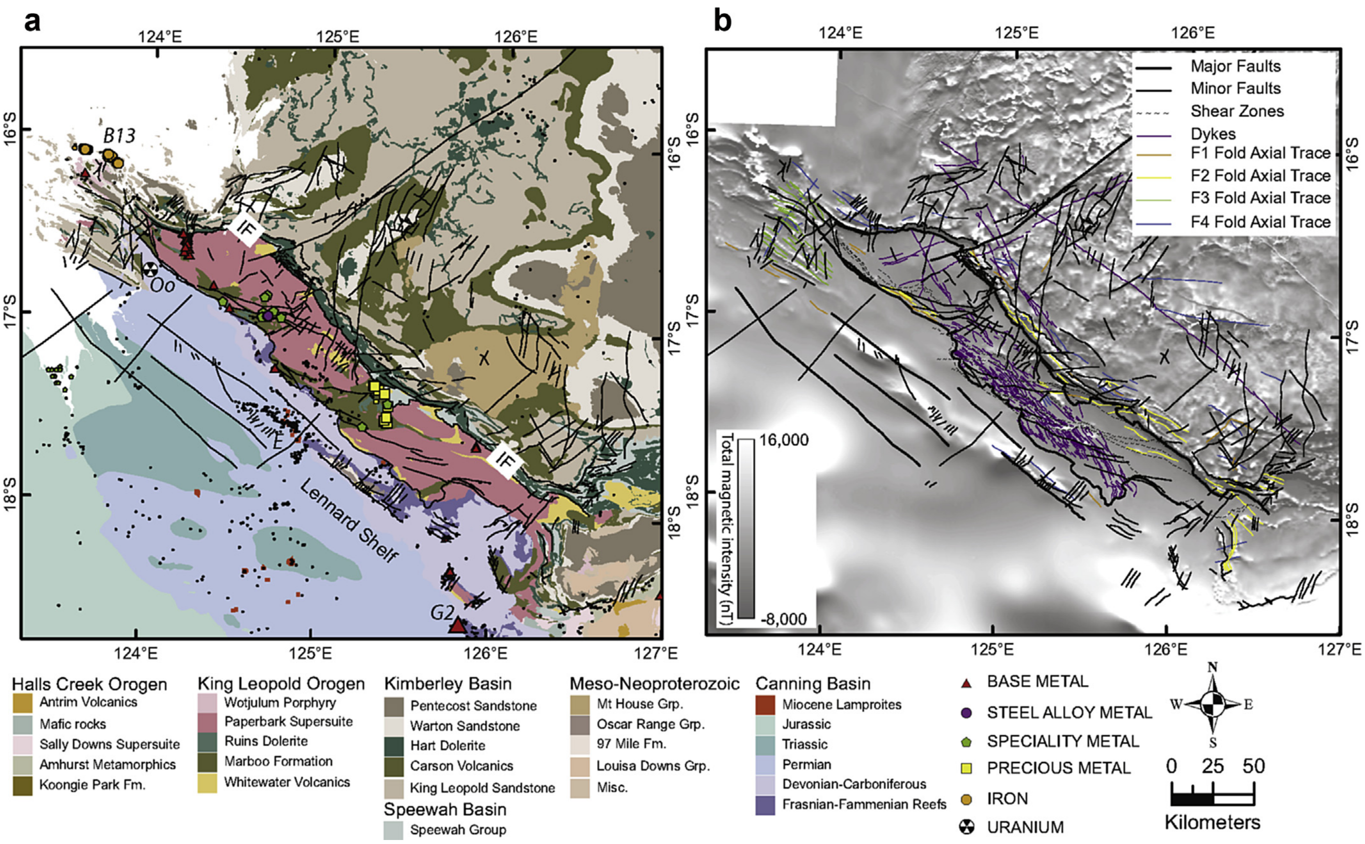

Figure 5. The King Leopold Orogen, showing (a) geology and mineral deposits/occurences. IF – Inglis Fault. Deposits are named as in Appendix B except for Uranium at Oobagooma (Oo) and the Ellendale diamond field (El). (b) The structural interpretation of Lindsay et al. (2015b).

period of "soft" collision and mutual basin formation, or the derivation of the Lander Rock Formation through erosion and re-deposition of the Tanami Group.

Little tectonic activity occurred after ca. 1800 Ma, with several phases of basin formation, interrupted by the Cambrian Kalkarindji LIP. Basins include the late Paleoproterozoic (1.77–1.64 Ga) Birrindudu Basin, the Neoproterozoic to early Cambrian Murrabba Basin (as part of the Centralian Superbasin (Haines and Allen, 2016)), the middle Cambrian to early Cretaceous Wiso Basin (Crispe et al., 2007) and finally the Canning Basin.

3.4.1. Mineralisation

Mineral deposits are overwhelmingly gold associated with the Tanami Orogeny. The Northern Territory contains several large deposits, including Callie, Groundrush, Buccaneer and Old Pirate but Western Australia hosts only one, Coyote (Bagas et al., 2014).

Almost all the gold deposits are hosted in the Dead Bullock Formation (Bagas et al., 2014). Coyote is somewhat unusual, as it is hosted in the Killi-Killi Formation (Bagas et al., 2014). Mineral systems analysis of this mineral system indicates that the major components are the presence of the reactive Dead Bullock Formation, GTO1 and 2 structures, and the relationship of these with crustal-scale listric faults and Paleoproterozoic basin architecture (Joly et al., 2012).

3.5. The west Arunta Orogen

The west Arunta Orogen includes the Aileron Province in the north, and the Warumpi Province in the south (Fig. 6). The Aileron Province is dominated by 1860–1700 Ma igneous and metamorphic rocks (Collins and Shaw, 1995), whereas the Warumpi Province is dominated by younger ca. 1690–1600 Ma igneous and metamorphic rocks (Scrimgeour et al., 2005; Hollis et al., 2013).

The oldest known rocks in the Aileron Province belong to the metasedimentary Lander Rock Formation. Detrital zircon populations of 1880–1840 Ma provide an upper age limit, and are the basis for correlation with the Killi-Killi Formation (Claoué-Long et al., 2008).

Two events occurred between 1810 Ma and 1770 Ma, overlapping in time with GTO-2 and the Yapunkgu Orogeny of the Rudall Province. The 1810–1790 Ma Stafford Event (Claoué-Long and Edgoose, 2008) and the 1780–1770 Ma Yambah Event (Collins and Shaw, 1995; Claoué-Long and Hoatson, 2005). Subsequently, a continental-arc setting has been suggested for the 1770–1750 Ma Inkamullah Igneous Event (Zhao and McCulloch, 1995; Claoué-Long and Hoatson, 2005). These studies suggest there was no major ca. 1800–1750 Ma collision in the Aileron Province, and the tectonic setting was likely the upper plate to a north-dipping subduction zone (Betts et al., 2011).

The 1730–1690 Ma Strangways Orogeny involves high-grade granitic magmatism and granulite facies metamorphism at >750 °C and ~8–9 kbar (Collins and Shaw, 1995). This event is commonly considered part of a wider-event that includes the Kimban Orogeny of the Gawler Craton (Hand et al., 2007) and possibly also the Nimrod and Yavapai orogenies in Antarctica and Laurentia respectively (Betts et al., 2011; Boger, 2011).

The Warumpi Province is separated from the Aileron Province by the Central Australian Suture (Goleby et al., 1990; Selway et al., 2009), and may extend beneath the Amadeus Basin (Korsch and Doublier, 2014). The 1690–1660 Ma Argilke Event was

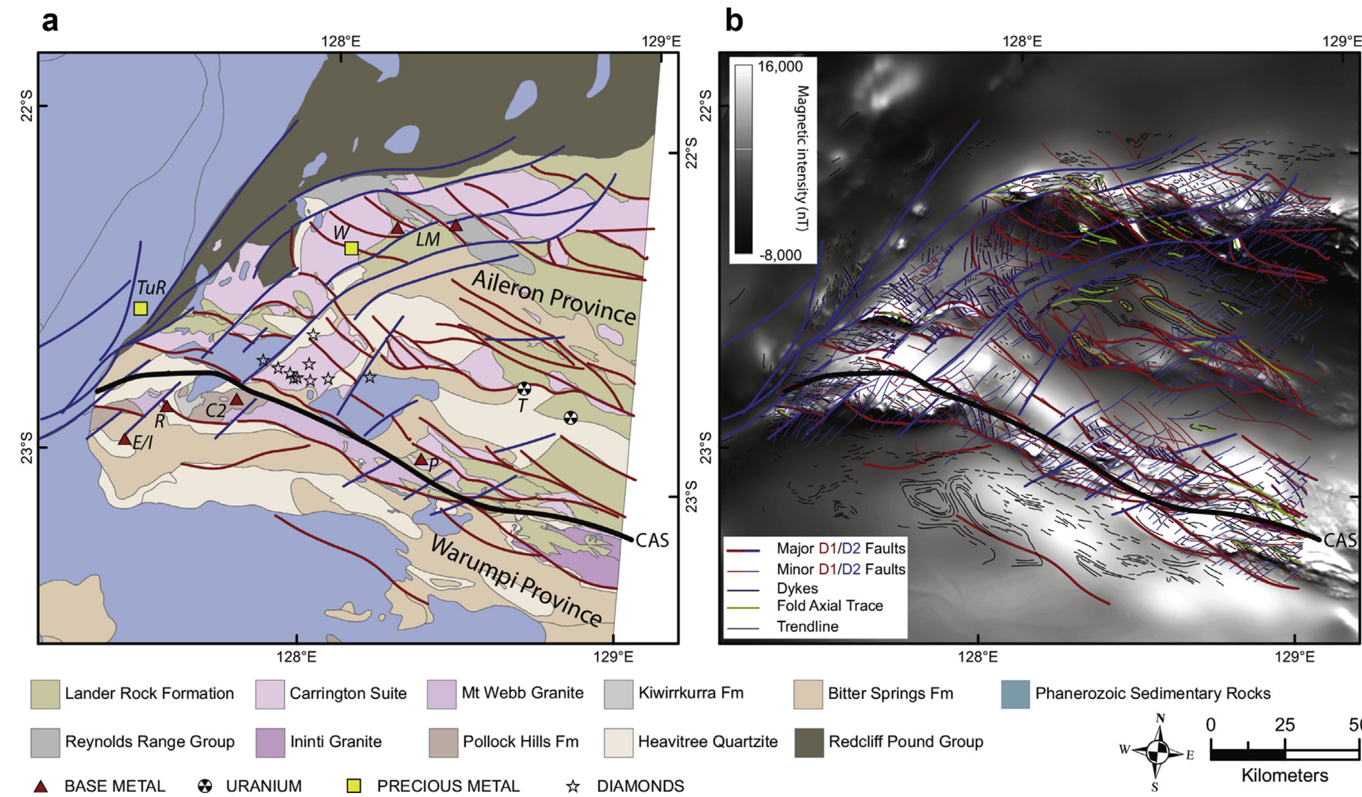

Figure 6. The west Arunta Province, showing (a) geology and mineral deposits/occurences. Copper-gold occurrences include Mt Webb (C2), Pokali (P), Lake Mackay (LM) and Webb (W); gold-silver mineralisation occurs at Top-Up-Rise (TuR); lead-zinc occurrences exist at Rhea (R), Enceladus (E) and Iapetus (I); Theseus (T) is a significant uranium deposit. Numerous diamond occurrences are clustered in the central part of the area. (b) The structural interpretation of Joly et al. (2015). CAS – Central Australian Suture.

characterised by juvenile felsic magmatism indicative of subduction (Collins and Shaw, 1995), whereas high-grade metamorphism, deformation and magmatism during the ca. 1640 Ma Liebig Orogeny may indicate an accretion event (Scrimgeour et al., 2005). Isotopic signatures suggest that the Warumpi Province may have been rifted from the Aileron Province prior-to or during the Argilke Event and subsequently re-attached during the Liebig Orogeny (Hollis et al., 2013).

Mesoproterozoic activity includes high-grade, high-temperature metamorphism and north-south shortening from two events, the ca. 1610–1570 Ma Chewings Orogeny (Collins and Shaw, 1995) and later ca. 1150–1080 Ma reworking (Morrissey et al., 2011). Lastly, dykes of the ca. 1076 Ma Stuart Pass Dolerite were intruded as part of the Warakurna LIP.

The Neoproterozoic was dominated by the formation of the Amadeus, Ngalia and Georgina Basins as part of the Centralian Superbasin (Walter et al., 1995). This basin records a broad subsidence from ca. 800 Ma to ca. 600 Ma (Zhao et al., 1994; Lindsay, 2002), and then foreland-basin style depositional sequences from ca. 600 Ma until ca. 350 Ma (Lindsay, 2002).

The last major orogenic event to have affected the Arunta Orogen is the episodic deformation of the ca. 450–350 Ma Alice Springs Orogeny (ASO). The ASO in the Arunta region involved fold-thrust sequences rooted in the evaporitic Bitter Springs Formation (Flottmann et al., 2005), and also crustal-scale deformation, including a ca. 20 km north-up Moho offset on the Redbank Thrust Complex (Goleby et al., 1989).

3.5.1. Mineralisation

A significant geochemical gold anomaly (Wyborn et al., 1998), and base-metal and gold occurrences are associated with the 1640 ± 7 Ma Mount Webb granite and the 1677 ± 6 Ma felsic volcanics of the Pollock Hills Formation. A second set of occurrences is located near Lake Mackay, associated with the ca. 1770 Ma Carrington Suite (Fig. 6). Lead-zinc mineralization in the Amadeus Basin nearby is associated with the Bitter Springs Formation. The west Arunta Orogen also hosts uranium and diamond deposits (see Joly et al., 2013 for details).

3.6. The west Musgrave Province and Madura Province

The west Musgrave Province preserves a largely Mesoproterozoic tectonic evolution from a subduction-proximal setting to a stable intracontinental region. The isotopic evolution of this region suggests a regionally significant crust forming event at ca. 1.9 Ga (Kirkland et al., 2012), but the first widely recognized magmatic event is from 1650 Ma to 1550 Ma (Camacho and Fanning, 1995; Edgoose et al., 2004; Wade et al., 2006; Kirkland et al., 2012). Relatively juvenile isotope signatures suggest the presence of a magmatic arc (Wade et al., 2006; Kirkland et al., 2012). This event may reflect the subduction zone stepping-back following the Liebig Orogeny (Aitken et al., 2016).

In the mid-Mesoproterozoic, two significant tectonic events are recognised; the ca. 1400 Ma Papulankutja magmatic intrusive event and the 1345–1293 Ma Mount West Orogeny (Howard et al., 2015). The Mount West Orogeny involved granitic magmatism, forming the Wankanki Supersuite, and the formation of a contemporaneous basin (Evins et al., 2012). These events may reflect an initial magmatic-arc setting transitioning to collision by ca. 1290 Ma (Howard et al., 2015).

Subsequent events were intraplate. The ca. 1220–1150 Ma Musgrave Orogeny involved prolonged ultra-high-temperature conditions and associated high-temperature A-type magmatism (Smithies et al., 2011). Approximate 1150 Ma magmatism is observed throughout central and southern Australia and conjugate Antarctic terranes, as a wider expression of the later stages of this event (Aitken and Betts, 2008).

From ca. 1085 Ma to 1040 Ma, the dominantly magmatic Giles Event occurred, likely in a rift setting (Howard et al., 2015; Smithies et al., 2015). The early stages of the Giles Event, from ca. 1085 Ma to ca. 1074 Ma, were characterised by mafic-ultramafic and bimodal magmatism. The Giles Suite includes enormous layered mafic-ultramafic intrusions, and also gabbroic intrusions and co-magmatic granitic rocks (Evins et al., 2010). Structures generated during this period are either magmatic or magmatism-associated (Aitken et al., 2013).

The later stages of the Giles Event, from ca. 1074 Ma to ~1040 Ma were characterized by extensive and voluminous felsic volcanic rocks, subvolcanic intrusives and granites (Howard et al., 2015; Smithies et al., 2015). This stage of the rift is also associated with a number of regional deformation events (Evins et al., 2010; Aitken et al., 2013).

At ca. 1070–1065 Ma, the extensive but short-lived Warakurna LIP (Wingate et al., 2004) overprinted the Giles Event with the intrusion of Alcurra Dolerite suite dykes and sills at ca. 1068 Ma. The Alcurra Dolerite suite is chemically distinct from the Giles Suite (Howard et al., 2009), and hosts several nickel-copper deposits and prospects (Maier et al., 2015).

Later tectonic events are dominated by subsidence and extension, as indicated by further mafic magmatism at ca. 825 Ma (Zhao et al., 1994) and the formation of the Officer and Amadeus Basins (Lindsay, 2002). This is punctuated by two intraplate orogenic events, the ca. 600–530 Ma Petermann Orogeny, and the ca. 450–300 Ma Alice Springs Orogeny. Neither of these is associated with regional magmatism. Petermann Orogeny reworking in the west Musgrave Province is focused in the north and northeast, where high-pressure metamorphic rocks are exhumed in a crustal-flow zone (Raimondo et al., 2009). Deformation and metamorphic grade reduce markedly towards the south east (Joly et al., 2014). Alice Springs Orogeny reworking may include thrusting at the southern margin (Lindsay and Leven, 1996) and the formation of small basins (Joly et al., 2014).

The Madura Province is the roughly triangular region that lies beneath the Eucla Basin, between the west Musgrave Province and the Albany Fraser Orogen (Fig. 1). Very little is known about this region, however, limited exploration drilling has recently revealed the dominance of ca. 1420–1400 Ma gabbroic and granitic rocks, the Haig Cave Supersuite. These rocks preserve juvenile magmatic signatures and are interpreted to represent an oceanic arc (Spaggiari et al., 2015). The Haig Cave Supersuite is contemporaneous with the Papulankutja Supersuite, and these may be different parts of the same subduction system (Aitken et al., 2016).

3.6.1. *Mineralisation*

Known commodities in the west Musgrave Province include nickel, copper, PGEs and vanadium for which deposits and prospects include Wingellina (Ni-Co-PGE), Nebo-Babel (Ni-Cu-PGE) and Succoth (Cu-Ni-PGE) (Joly et al., 2014; Maier et al., 2015). These orthomagmatic deposits are all associated with mafic/ultramafic magmatic rocks, either the 1085–1075 Ma Giles Suite or the ca. 1067 Ma Alcurra Dolerite suite (Maier et al., 2015).

Several hydrothermal base metals and gold mineralisation prospects exist, including Tollu (Cu-Co-Ni), Voyager (Au-Cu), and Handpump/Primer (Au-Mo). These deposits are typically hosted in brecciated volcanic rocks of the upper Bentley Supergroup, and were likely deposited during this structurally complex rift event.

Within the Madura Province, potential is indicated for Ni-Co-Cu (e.g. Burkin prospect), and for base-metals, precious metals, and PGEs (Loongana prospects) within the Haig Cave Supersuite of the Loongana Arc, and for gold-copper (e.g. Moodini prospect) in ca. 1180 Ma granitoids (Spaggiari et al., 2015).

3.7. *The Albany Fraser Orogen*

The Albany Fraser Orogen forms the southeastern margin of the Yilgarn Craton, and was built upon a Yilgarn-like Archean basement (Nelson et al., 1995; Clark et al., 2000; Kirkland et al., 2011). The orogen comprises several distinct tectonic zones with differing histories (Occhipinti et al., 2014; Spaggiari et al., 2014). The Northern Foreland represents reworked Yilgarn Craton, variably deformed during the Albany Fraser Orogeny. The Kepa-Kurl Booya Province represents the basement to the Albany Fraser Orogen, and is further subdivided into the Tropicana, Biranup, Fraser and Nornalup Zones (Fig. 3).

The Tropicana Zone is a distinct part of the Yilgarn Craton that may include a Neoarchean passive margin sequence. The Tropicana Gneiss was metamorphosed at up to granulite facies and then uplifted to greenschist facies by 2515 Ma (Blenkinsop and Doyle, 2014; Occhipinti et al., 2014), during which time the Tropicana gold deposit formed. The Tropicana Zone underwent further reworking during the Palaeoproterozoic and again during the late Mesoproterozoic Albany-Fraser Orogeny stage II.

The Biranup, Fraser and Nornalup Zones preserve a number of tectonic events that have variably affected each zone. Early magmatism has been recognised in the 1810–1800 Ma Salmon Gums Event and the 1780–1760 Ma Ngadju Event. Although their tectonic settings are uncertain, these events coincide with the earliest stages of the Barren Basin, and they may represent rift events. The better defined Biranup Orogeny at 1710–1650 Ma may also represent a continental rift event (Kirkland et al., 2011; Spaggiari et al., 2014, 2015). The Barren Basin was deposited on the Albany Fraser province from 1815 Ma to 1600 Ma, in a setting interpreted to have evolved from a rift-basin to a passive margin through this time (Spaggiari et al., 2015). The continent-scale tectonic setting of these events is not entirely clear, but they may possibly be driven by northwest-dipping subduction processes at the margin of Columbia (Aitken et al., 2016).

From 1600 Ma to 1305 Ma, the Arid Basin was deposited on the passive margin and the adjacent oceanic plate (Spaggiari et al., 2015). This hiatus coincides with subduction-related tectonic activity in the Musgrave and Madura provinces, perhaps indicating east-dipping subduction (Aitken et al., 2016). This persisted until the Albany Fraser Orogeny stage I occurred from ca. 1330–1260 Ma (Clark et al., 2000; Bodorkos and Clark, 2004). During this time, overall subduction may have returned to west-dipping (Aitken et al., 2016).

The effects of Stage I of the Albany Fraser Orogeny were widespread, but are especially significant in the mafic-dominated Fraser Zone, which formed between 1305 Ma and 1290 Ma, likely as a result of rifting (Spaggiari et al., 2014). The Biranup Zone preserves very little Stage I activity. Throughout the Nornalup Zone, Stage I is defined by pervasive high-grade metamorphism, ductile deformation and the intrusion of the granitic and gabbroic rocks of the Recherche Supersuite (Spaggiari et al., 2014).

The upper Arid Basin contains detritus that has dissimilar provenance to local sources, but has similar provenance to the Madura Province (Spaggiari et al., 2015), and possibly also the Musgrave Province, suggesting convergence of these regions prior to peak metamorphism at ~1310–1290 Ma (Nelson et al., 1995). Following collision, the Ragged Formation was deposited between ca. 1305 Ma and 1175 Ma (Spaggiari et al., 2014).

Stage II of the Albany Fraser Orogeny, from 1225 Ma to 1140 Ma, is characterized by further high-grade metamorphism and extensive granitic magmatism, although the effects vary significantly throughout the province. This event was probably intraplate and shares many characteristics with the contemporaneous Musgrave Orogeny (cf. Spaggiari et al., 2014; Howard et al., 2015). Following Stage II, the Albany Fraser Province has been generally quiescent.

3.7.1. Mineralisation

The Albany Fraser Orogen has few known mineral deposits compared to similarly sized orogens elsewhere. The Northern Foreland and the Tropicana Zone possess mostly Archean deposits, including orogenic gold at Tropicana. These regions also contain Paleoproterozoic precious-metal (Voodoo Child Au-Ag, Hercules Au) and CD-SHBM deposits (Trilogy Pb-Zn-Ag-Cu-Au) within the Barren Basin (Tyler et al., 2014). In the Fraser Zone, the recent discovery of Nova-Bollinger suggests regional prospectivity for this ore-deposit type. No deposits are known from either the Biranup or Nornalup Zones.

4. Time scales of Western Australian Proterozoic mineral systems

Based on major changes in the locus and type of tectonic activity in WA, we define seven stages in the tectonic development of Proterozoic Western Australia. These are temporally correlated with the global supercontinent cycle (Fig. 2). Rocks within WA also provide evidence for major changes in the atmosphere and hydrosphere. Regional tectonic settings are superimposed on these global influences, and together, these act to generate tendencies towards particular ore-deposit type.

In this section, a high-level classification of the likelihood of formation of several styles of ore deposit is estimated for each region and stage. We note that likelihood of formation is not the same as likelihood of presence, and certainly not likelihood of detection. Furthermore, the method is kept simple, so as to provide consistency across the regions. Important details may be missed in a simple analysis, however, such details are likely to be known only in the better studied regions, and the attempt to include such details leads to bias in the results.

The likelihood estimate is based on both global secular influences, and the region's inferred tectonic setting(s), for each of which a formation-likelihood score is given. The possible scores are 0 (unlikely), 1 (less likely) or 2 (more likely), see Appendix A. The statements below articulate the meaning of these terms:

0 – "Deposits are not observed in this period/setting, or are only observed in a few exceptional cases"
1 – "Deposits are observed in this period/setting, but they are not fundamental to global resource endowment for that deposit type"
2 – "Deposits from this period/setting are fundamental to global resource endowment for that deposit type"

The broad categories for analysis often encompass both highs and low likelihoods, for example a significant peak may occur

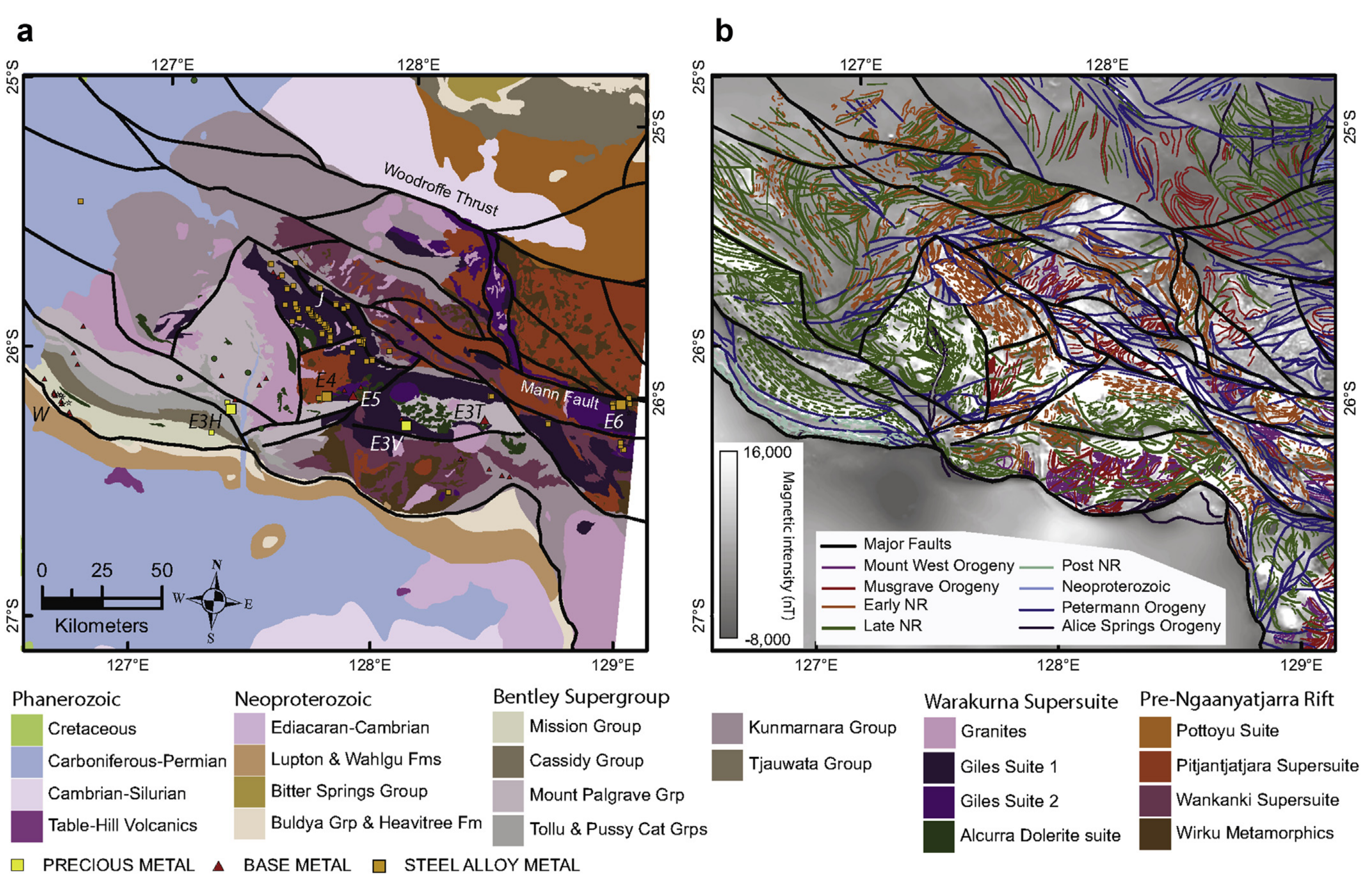

Figure 7. The west Musgrave Province, showing (a) geology and mineral deposits/occurences. Deposits are labelled as per Appendix B, with in addition, numerous vanadium-titanium-iron occurences in the Jameson intrusion (J) and copper occurences around Warburton (W). (b) The structural interpretation of Joly et al. (2014) showing the interpreted age of structures (last motion).

within a period of generally low-endowment, or particular sub-categories of tectonic settings may be more or less prospective. Rather than add complexity to the analysis, we take the view that if a sub-category is well endowed, then that endowment is conferred upwards to the category.

On the basis that both must be favourable for ore deposit formation, the secular likelihood and tectonic setting likelihood scores are combined by returning the lower likelihood score. Note that each ore deposit type is considered independently from the others, and therefore these relative terms do not allow comparison between ore-deposit types.

The results of these analyses are compared with the known tectonic record of Western Australia to identify: (1) more or less likely ore deposit types that are indeed recognized; (2) more or less likely ore-deposit types that are missing from the record and; (3) unlikely ore-deposit types that nevertheless are identified. All of these, but especially the last two, present avenues to develop a better understanding of Proterozoic ore-forming processes.

4.1. Stage 1 – Columbia assembly (2.22–1.95 Ga)

The assembly of the West Australian Craton (WAC) involved the ca. 2.2 Ga Opthalmia Orogeny and the 2.0 Ga Glenburgh Orogeny, which affected the Capricorn Orogen and the proximal parts of the Yilgarn and Pilbara Cratons (Fig. 3). The Kimberley Craton and parts of the Albany Fraser Orogen also existed at this time.

With the inferred tectonic settings, ore-deposit likelihoods are low in the Kimberley Craton and Albany Fraser orogen, although the latter preserves the Hercules deposit (A5). High likelihoods are suggested in the Capricorn Orogen region for several styles of ore deposits (Fig. 8). This includes orogenic gold in the convergent margins and intrusion-related gold-copper in convergent margins, retro-arc regions and rift zones. The convergent margin of the Glenburgh Orogeny preserves the Glenburgh deposit (A1) and the Harmony-Peak Hill deposits (A2). The setting of Harmony-Peak-Hill is uncertain, but Glenburgh developed in the arc-related Dalgaringa Supersuite, and was metamorphosed later in the same orogeny (Roche et al., 2017).

The very end of this time period contains the onset of a notable peak in the global record of VHMS deposits (Huston et al., 2010). Overall likelihood is high therefore in suitably-aged back-arc and rift settings (Fig. 8). VHMS deposits formed in the Bryah rift basin at ca. 2 Ga at Degrussa (A3) and at Horseshoe Lights (A4) (Hawke et al., 2015).

Although the dating is relatively poorly constrained, the upgrading of Hamersley BIF to martite-microplaty hematite ore likely occurred at ca. 2050–2000 Ma (Müller et al., 2005). Iron formations of this age are observed in the Bryah Basin, although currently no economic deposits exist.

Unobserved high-likelihood ore deposit types for this time period include IOCGs, Ni-Cu and PGE in continental rifts. Rifting events lack A-type magmatism, and so IOCGs are not likely. Potential for Ni-Cu-PGE deposits exists in the mafic units within the Yerrida and Bryah basins, although currently no deposits are known.

The likelihood estimate for sedimentary-hosted base metals (SHBMs) is moderate because, although favourable settings exist, this time period is not a notable peak in the global record (Leach et al., 2010). Nevertheless, some potential may exist within the Yerrida and lower-Earaheedy basins. Carbonates of the lower-Earaheedy Basin, deposited between 2000 Ma and 1950 Ma (Sheppard et al., 2016), host the Magellan base-metal deposit (B2). Dating of xenotime and monazite associated with Magellan has returned a date of 1815 ± 13 Ma (Muhling et al., 2012), consistent with forming during the Capricorn Orogeny, but an earlier system associated with the later Glenburgh Orogeny is also feasible.

4.2. Stage 2 – Columbia assembly (1.95–1.77 Ga)

This stage coincided with the final assembly of Columbia. In WA it involved the amalgamation of the Kimberley, North Australian and West Australian cratons into a single entity. During this stage, global peaks are observed in orogenic gold and VHMS (Groves et al., 2005a; Goldfarb et al., 2010; Huston et al., 2010). Moreover, the tectonic setting of Australia included a long convergent margin at the margin of the North Australian Craton (Betts et al., 2016), giving high overall likelihoods for ore-deposit types that relate to this tectonic setting (Fig. 9).

The Paterson, King Leopold, Halls Creek, Tanami and Arunta orogens all preserve evidence for a convergent margin to retro-arc setting during this stage, with embedded rifting events (Fig. 3). This suggests a high likelihood for orogenic gold and VHMS in the

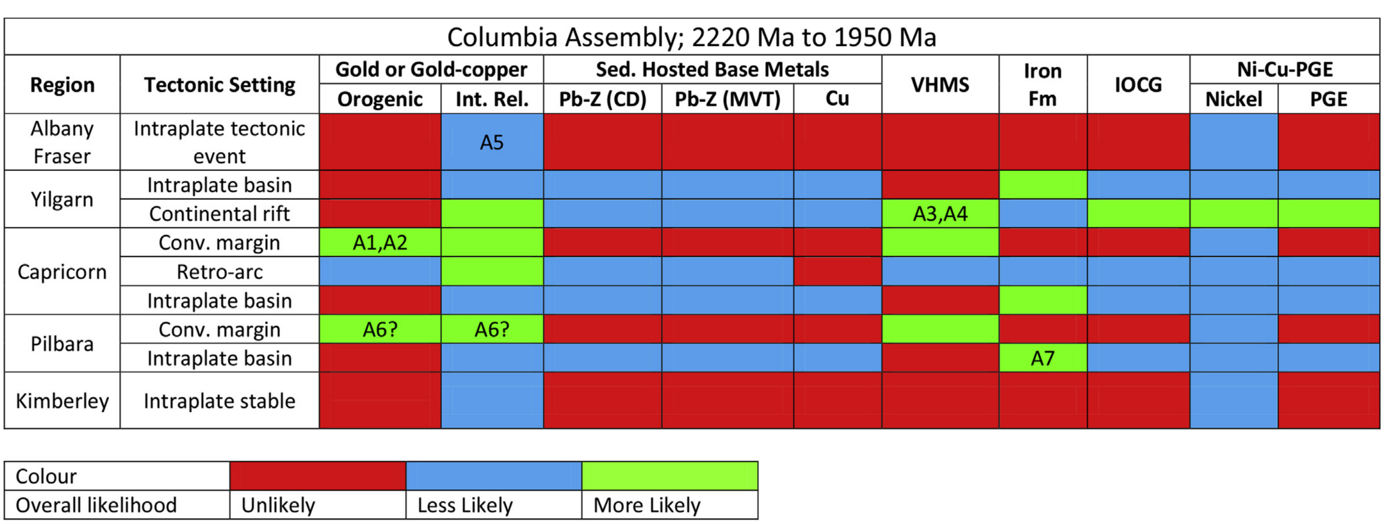

Figure 8. 2.2–1.95 Ga ore deposit likelihood from secular and tectonic influences. See text and Appendix A for derivation of likelihood. Deposits are listed in Appendix B.

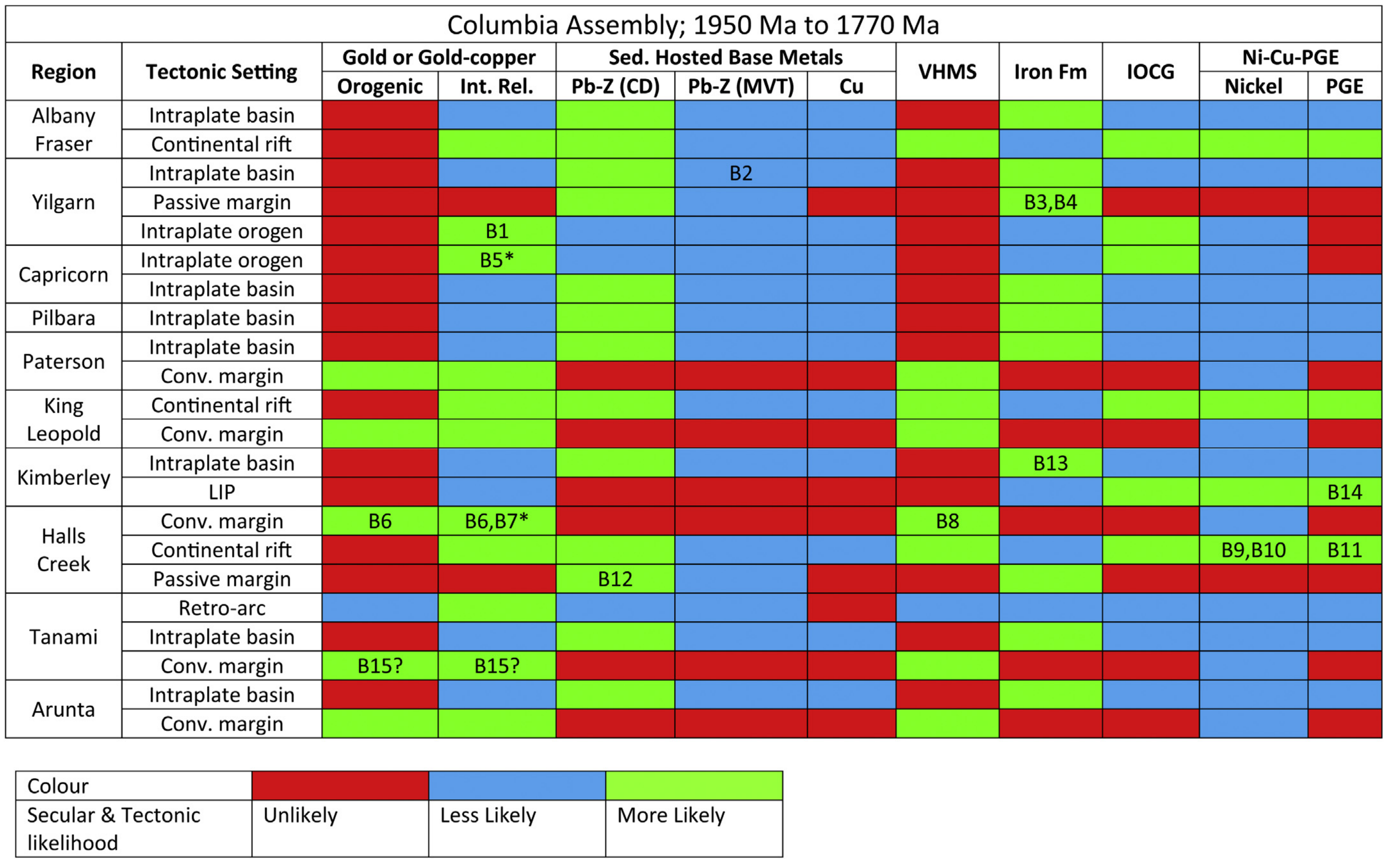

Figure 9. 1.95–1.77 Ga ore deposit likelihood from secular and tectonic influences. See Appendix A for derivation of likelihood. Deposits are listed in Appendix B. Asterisks indicate approximate classification only.

convergent margin regions, and for VHMS, intrusion related gold-copper, and Ni-Cu-PGE in the rifted regions.

Gold mineralization is prominent in the Tanami Orogen (Bagas et al., 2014), including Coyote (B15). The ca. 1800 Ma Tanami gold mineral system is widely considered to be orogenic (Bagas et al., 2010), although tectonic considerations may suggest an intraplate setting. Gold is also widespread, although less economically significant, in the Kimberley region (B6, B7) associated with the Hooper and the Halls Creek orogenies (Lindsay et al., 2015a; Occhipinti et al., 2016). The Capricorn Orogen also preserves intrusion-related gold deposits (B1) that probably date to the Capricorn Orogeny (Hawke et al., 2015).

Neither the Yapungku Orogeny (Paterson) nor the Stafford and Yambah Events (Arunta) are currently associated with gold ore deposits, despite a high likelihood estimate. In each case, and in contrast to the Kimberley and Tanami regions, both these regions are substantially reworked (Fig. 3), and preservation potential is reduced due to erosion and metamorphism. Nevertheless, potential may exist for Paleoproterozoic gold deposits in the parts of these orogens less affected by later tectonic events.

Globally, a prominent peak is observed for the formation of VHMS deposits between 2000 Ma and 1800 Ma (Huston et al., 2010). During this period both the Kimberley and Tanami regions saw the formation of rifts, including potentially VHMS prospective volcanic-sedimentary units in the ca. 1840 Ma Koongie Park Formation and the ca. 1865 Ma Dead Bullock Formation. The Koongie Park Formation includes interpreted VHMS deposits at Koongie Park and associated deposits (B8) (Occhipinti et al., 2016). The Dead Bullock Formation of the Tanami Orogen likely formed in a back-arc rift setting (Bagas et al., 2008; Joly et al., 2010; Li et al., 2013), favourable for VHMS deposits. None are observed, but significant potential may exist, provided there is no local inhibitor of ore formation or preservation.

This stage has a fairly high abundance in nickel platinum and palladium (Naldrett, 2010). In Western Australia, major igneous complexes of this age are found only in the North Australian Craton. Mafic intrusions in the Halls Creek Orogen contain several Ni-Cu-PGE deposits, including Savannah (B9), Copernicus (B10) and Panton (B11). The ca. 1800 Ma Kimberley Group hosts the ca. 1800 Ma Hart Dolerite, which is generally prospective for Ni-Cu-PGE, and hosts vanadium and fluorite at Speewah (B14). The lack of nickel mineralization in other active regions, such as the Albany Fraser, Tanami and Capricorn orogens may be explained by the overall lack of mafic magmatism, in particular a lack of large mafic-ultramafic intrusions.

This stage encompasses the beginning of the major peak in CD-SHBM deposit endowment that extends from ca. 1.85 Ga to 1.4 Ga (Leach et al., 2010), and so likelihood is relatively high (Fig. 7). In the Kimberley region, a few CD-SHBM prospects have been discovered in the passive-margin related Biscay Formation, e.g. Ilmars (B12), and there is potential also in the overlying Olympio Formation (Occhipinti et al., 2016). MVT-style SHBMs are less likely (Leach et al., 2010), but nevertheless the carbonate-hosted Magellan deposit (B3) formed as a result of the Capricorn Orogeny (Muhling et al., 2012).

This stage also encompasses a significant peak in the global evolution of iron-formations from ca. 1.9 Ga to 1.8 Ga (Bekker et al., 2010). Correspondingly, major iron-formations were formed in passive margin or intraplate basin settings on the northern margin of the Yilgarn Craton, including in the Earaheedy (B3) and Padbury

(B4) basins. In general these iron formations do not yield economic deposits, but the west Kimberley region preserves some more significant iron-ore deposits hosted in the ca. 1800–1770 Ma Yampi Formation (B13).

4.3. Stage 3 – Columbia outgrowth (1.77–1.6 Ga)

Following the Yapungku and Yambah orogenies, the evolution of Australia was dominated by subduction systems active at the southern and eastern margins of the continent (Betts et al., 2016). This stage lasted from 1.77 Ga to ca. 1.6 Ga.

Globally, this time period sees high endowment for some ore-deposit types, but also significant reductions in the endowment for others. After ca. 1800 Ma, iron-formations are largely absent (Bekker et al., 2010), and VHMS and orogenic gold deposits become much less common until the mid-Neoproterozoic (Groves et al., 2005a; Goldfarb et al., 2010; Huston et al., 2010). Conversely, CD-SHBM deposits peak during this period (Leach et al., 2010).

Western Australia, in general, preserves little evidence for ore-genesis at this time, reflecting its mostly intraplate tectonic settings. Ore deposit types with relatively elevated likelihood in these regions include CD-SHBM in continental rifts and intraplate basins and intrusion-related gold-copper in intraplate orogens and rifts (Fig. 10).

The most promising environment for CD-SHBMs is typically within a rift or at a passive margin, however, Australia hosts several deposits, including Broken Hill, Mount Isa and Century that formed within the Isa Superbasin (Leach et al., 2010). Ore deposit formation peaked between ~1655 Ma and 1635 Ma coincident with the Liebig Orogeny, and then again at ca. 1590 Ma, coincident with the early stages of the Isan Orogeny (Leach et al., 2010). These dates suggest that far-field tectonic trigger events are important. CD-SHBM potential exists in several parts of WA, including the ca. 1815–1600 Ma Barren Basin of the Albany-Fraser Province, which hosts the Trilogy deposit (C4). The Barren Basin evolved from a rift towards a passive margin during this time, but also experienced several phases of shortening, e.g. the 1680 Ma Zanthus event (Spaggiari et al., 2015). The ca. 1735–1640 Ma Birrindudu Basin overlaps in time with and may be continuous with the highly endowed McArthur Basin. Finally, the Edmund Basin of the Capricorn Orogen was deposited between 1679 Ma and 1455 Ma. CD-SHBM deposits are not widely observed, but the 1594 ± 10 Ma Abra deposit (D2) and its surrounding region have experienced significant mineralisation. Mineralisation at Abra post-dates the main ore-forming event in the Isa Superbasin, but coincides with the later phase at ca. ~1590 Ma.

Intrusion-related gold-copper deposits may have been generated in regions affected by rifting and in particular intraplate orogenesis (Lang and Baker, 2001; Hart, 2007). Such regions include the Capricorn Orogen, which hosts the 1738 ± 5 Ma Mount Olympus gold-silver deposit (C1), and the Albany Fraser Province, which hosts the ca. 1750 Ma Voodoo Child deposit (C3). The west Arunta Orogen possesses Cu-Au-Ag mineralization at Mt Webb (C2), associated with a 1639 ± 5 Ma granitic intrusion, and was likely formed as a consequence of the Liebig Orogeny.

The Arunta Province and west Musgrave Province are interpreted to be in a plate-margin proximal and possibly convergent-margin setting during this period (Fig. 3). The likelihood of orogenic gold and VHMS deposits is only moderate, due to low secular likelihood. Higher-potential regions may be preserved in areas that have escape Mesoproterozoic reworking.

4.4. Stage 4 – Columbia to Rodinia transition (1.6–1.29 Ga)

Globally, this phase in the supercontinent cycle is among the least endowed with ore-deposits (Fig. 2), and this is reflected in Western Australia (Fig. 3). Tectonic activity occurred predominantly in the west Musgrave and Madura provinces and in the Albany Fraser Orogen (Fig. 3). Convergent plate-margin and retro-arc settings during this period may have potential for orogenic gold and VHMS deposits. However, this period coincides with global minima for these ore-deposit types (Groves et al., 2005a; Huston et al.,

Columbia Outgrowth; 1770 Ma to 1600 Ma											
Region	Tectonic Setting	Gold or Gold-copper		Sed. Hosted Base Metals			VHMS	Iron Fm	IOCG	Ni-Cu-PGE	
		Orogenic	Int. Rel.	Pb-Z (CD)	Pb-Z (MVT)	Cu				Nickel	PGE
Albany Fraser	Continental rift		C3	C4?							
	Intraplate basin			C4?							
	Passive Margin			C4?							
Yilgarn	Intraplate stable										
Capricorn	Intraplate orogen		C1								
	Intraplate basin										
Pilbara	Intraplate stable										
Paterson	Intraplate stable										
King Leopold	Intraplate stable										
Kimberley	Intraplate stable										
Halls Creek	Intraplate basin										
Tanami	Intraplate basin										
Arunta	Conv. margin		C2								
West Musgrave	Conv. margin										

Colour			
Secular & Tectonic likelihood	Unlikely	Less Likely	More Likely

Figure 10. 1.77–1.6 Ga ore deposit likelihood from secular and tectonic influences. See Appendix A for derivation of likelihood. Deposits are listed in Appendix B.

2010) and so the overall likelihood of these deposits is only moderate (Fig. 11).

Isotopic studies within the Musgrave and Albany Fraser regions indicate little new crust generation (Kirkland et al., 2011, 2012), perhaps inhibiting the formation of orogenic gold and VHMS deposits. Both these regions have also been metamorphosed to high-grade during later events (Clark et al., 2000; Howard et al., 2015), severely limiting preservation potential. Although unexposed, and only minimally explored, the Madura Province preserves a significant crust-forming event in the Loongana Arc, as well as experiencing lower-grades during subsequent events (Spaggiari et al., 2015). This region has perhaps the best potential for VHMS and orogenic gold deposits from this stage (Fig. 11).

Potential exists for CD-SHBM deposits up until ca. 1.4 Ga. Several basins overlap this time period, including the Edmund Basin, discussed previously, the ca. 1600–1350 Ma Arid Basin, likely in a passive-margin to oceanic environment (Spaggiari et al., 2015), and the ca. 1345–1290 Ma Ramarama Basin likely in an arc-proximal setting (Evins et al., 2012). Neither the Arid nor the Ramarama basins possess known CD-SHBM ore deposits, although both basins are metamorphosed and deformed, so limiting preservation potential.

Intraplate regions provide moderate to high likelihoods for intrusion-related gold-copper systems. Epithermal copper at Thaduna (D1) may represent one such system, linked with ca. 1465 Ma magmatic magmatism (Hawke et al., 2015).

The global abundances of nickel platinum and palladium for this stage are generally moderate, perhaps due to the relatively low occurrence of large mafic LIPs. Significant deposits at Voisey's Bay (1.33 Ga) and Kabanga (ca. 1.275 Ga), suggest that substantial potential may exist in suitable environments. Rift and LIP environments from this time period are rare within Western Australia (Fig. 3), but a notable exception is the mafic-dominated Fraser Zone of the Albany Fraser Orogen. This probable rift zone formed between 1305 and 1290 Ma, and hosts the world-class Nova-Bollinger deposit (D3), providing further support for a global metallogenic event at ca. 1.3 Ga.

This stage coincides with one of the major IOCG forming events, the ca. 1.59 Ga Olympic Province, which includes several large deposits within Southern and Northern Australia (Groves et al., 2010; Hayward and Skirrow, 2010). At 1.59 Ga, Western Australia was continuous with Northern Australia and preserves many geological commonalities. Despite this, Western Australia currently has no known IOCG deposits. Small IOCG-like prospects occur in the Northern Territory within the eastern Arunta Orogen (Huston et al., 2010).

IOCG deposits form in intraplate settings, over large-scale lithospheric discontinuities. Such favourable zones for IOCG formation were certainly present within Western Australia during this stage. As well as favourable architecture a geodynamic trigger is needed to cause the magmatic events that form large IOCG deposits. The giant IOCG ore-forming magmatic event of the Gawler Craton may be related to a lithospheric delamination event triggered by the onset of shallow-slab subduction (Hayward and Skirrow, 2010), or alternatively plume modified subduction (Betts et al., 2009). The dominant subduction systems in Australia from 1.65 Ga to 1.4 Ga

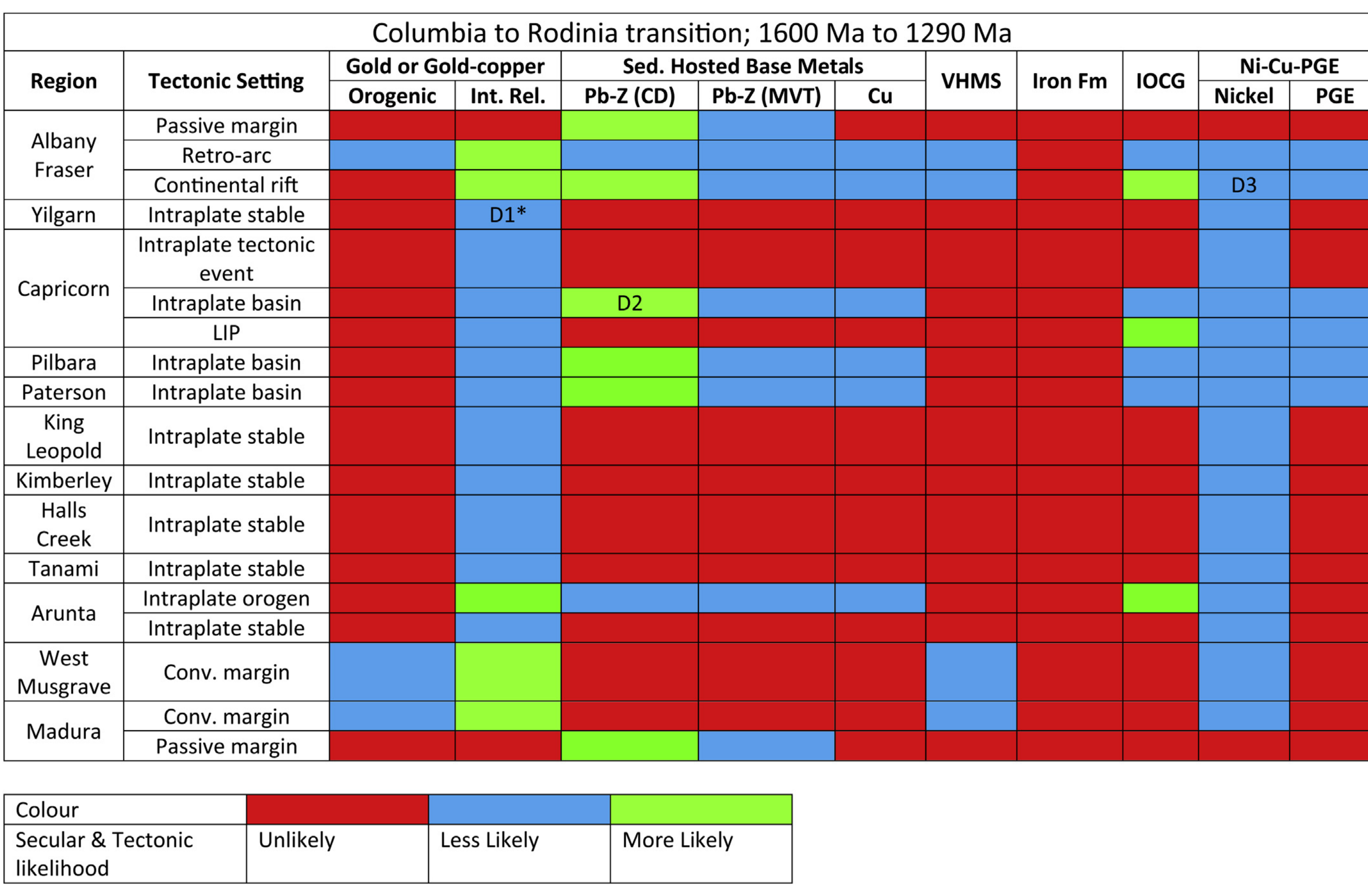

Figure 11. 1.6–1.29 Ga ore deposit likelihood from secular and tectonic influences. See Appendix A for derivation of likelihood. Deposits are listed in Appendix B. Asterisks indicate approximate classification only.

Rodinia Stability; 1290 Ma to 850 Ma											
Region	Tectonic Setting	Gold or Gold-copper		Sed. Hosted Base Metals			VHMS	Iron Fm	IOCG	Ni-Cu-PGE	
		Orogenic	Int. Rel.	Pb-Z (CD)	Pb-Z (MVT)	Cu				Nickel	PGE
Albany Fraser	Intraplate orogen	Red	Green	Blue	Blue	Blue	Red	Red	Blue	Blue	Red
	Intraplate basin	Red	Blue	Blue	Blue	Blue	Red	Red	Blue	Blue	Blue
Yilgarn	LIP	Red	Blue	Red	Red	Red	Red	Red	Blue	Green	Green
Capricorn	Intraplate tectonic event	Red	Blue	Red	Red	Red	Red	Red	Red	Blue	Red
	Intraplate basin	Red	Blue	Blue	Blue	Blue: E1*,E2*	Red	Red	Blue	Blue	Blue
	Intraplate orogen	Red	Green	Blue	Blue	Blue	Red	Red	Blue	Blue	Red
	LIP	Red	Blue	Red	Red	Red	Red	Red	Blue	Green	Green
Pilbara	LIP	Red	Blue	Red	Red	Red	Red	Red	Blue	Green	Green
Paterson	Intraplate basin	Red	Blue	Blue	Blue	Blue	Red	Red	Blue	Blue	Blue
King Leopold	Intraplate tectonic event	Red	Blue	Red	Red	Red	Red	Red	Red	Blue	Red
Kimberley	Intraplate tectonic event	Red	Blue	Red	Red	Red	Red	Red	Red	Blue	Red
Halls Creek	Intraplate tectonic event	Red	Blue	Red	Red	Red	Red	Red	Red	Blue	Red
Tanami	Intraplate stable	Red	Blue	Red	Red	Red	Red	Red	Red	Blue	Red
Arunta	Intraplate orogen	Red	Green	Blue	Blue	Blue	Red	Red	Blue	Blue	Red
West Musgrave	Intraplate orogen	Red	Green	Blue	Blue	Blue	Red	Red	Blue	Blue	Red
	Continental rift	Red	Green: E3	Blue	Blue	Blue	Blue	Red	Blue	Green: E6	Green: E6
	LIP	Red	Blue	Red	Red	Red	Red	Red	Blue	Green: E4,E5	Green
Madura	Intraplate orogen	Red	Green	Blue	Blue	Blue	Red	Red	Blue	Blue	Red

Colour	Red	Blue	Green
Secular & Tectonic likelihood	Unlikely	Less Likely	More Likely

Figure 12. 1.29–0.85 Ga ore deposit likelihood from secular and tectonic influences. See Appendix A for derivation of likelihood. Deposits are listed in Appendix B. Asterisks indicate approximate classification only.

were a west-dipping subduction system beneath the continent's eastern margin, and a system in the Musgrave and Madura Provinces (Aitken et al., 2016). The former may have generated compressional deformation within the eastern part of the continent (Hayward and Skirrow, 2010), but it is probably too distant to have significantly affected Western Australia. The lack of early- to mid-Mesoproterozoic orogenesis within western and north-western Australia suggests that the central Australian subducting slab was

Rodinia Breakup; 850 Ma to 650 Ma											
Region	Tectonic Setting	Gold or Gold-copper		Sed. Hosted Base Metals			VHMS	Iron Fm	IOCG	Ni-Cu-PGE	
		Orogenic	Int. Rel.	Pb-Z (CD)	Pb-Z (MVT)	Cu				Nickel	PGE
Albany Fraser	Intraplate stable	Red	Blue	Red	Red	Red	Red	Red	Red	Blue	Red
Yilgarn	Intraplate stable	Red	Blue	Red	Red	Red	Red	Red	Red	Blue	Red
Capricorn	LIP	Red	Blue	Red	Red	Red	Red	Blue	Blue	Blue	Blue
Paterson	Intraplate basin	Red	Blue	Blue	Blue	Green: F1	Red	Blue	Blue	Blue	Blue
King Leopold	Intraplate basin	Red	Blue	Blue	Blue	Green	Red	Blue	Blue	Blue	Blue
Kimberley	Intraplate basin	Red	Blue	Blue	Blue	Green	Red	Blue	Blue	Blue	Blue
Halls Creek	Intraplate basin	Red	Blue	Blue	Blue	Green	Red	Blue	Blue	Blue	Blue
Tanami	Intraplate basin	Red	Blue	Blue	Blue	Green	Red	Blue	Blue	Blue	Blue
Arunta	Intraplate basin	Red	Blue	Blue	Blue	Green	Red	Blue	Blue	Blue	Blue
West Musgrave	Intraplate basin	Red	Blue	Blue	Blue	Green	Red	Blue	Blue	Blue	Blue
	LIP	Red	Blue	Red	Red	Red	Red	Blue	Blue	Blue	Blue
Madura	Intraplate basin	Red	Blue	Blue	Blue	Green	Red	Blue	Blue	Blue	Blue

Colour	Red	Blue	Green
Secular & Tectonic likelihood	Unlikely	Less Likely	More Likely

Figure 13. 0.85–0.65 Ga ore deposit likelihood from secular and tectonic influences. See Appendix A for derivation of likelihood. Deposits are listed in Appendix B. Asterisks indicate approximate classification only.

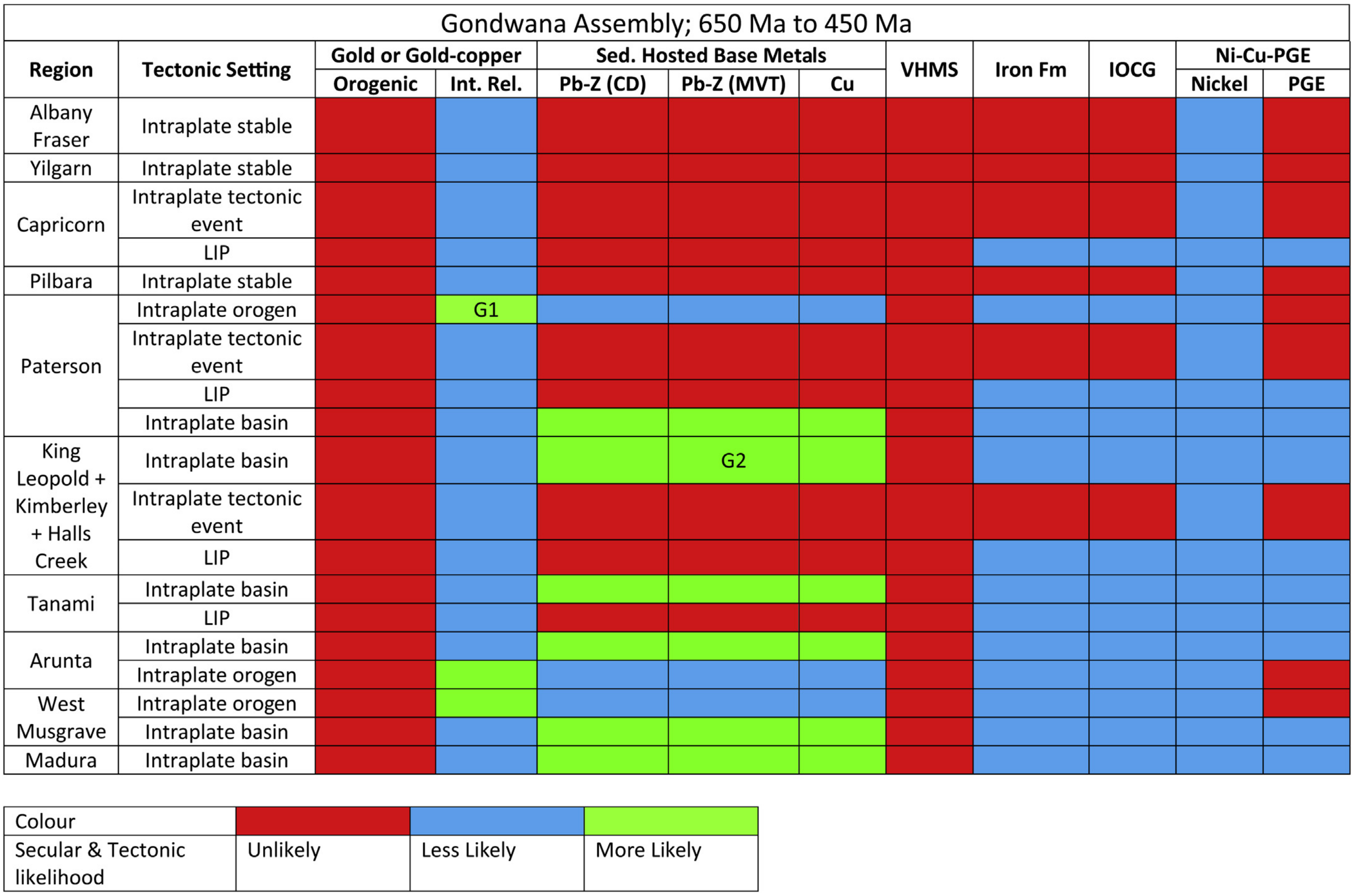

Figure 14. 0.65–0.45 Ga ore deposit likelihood from secular and tectonic influences. See Appendix A for derivation of likelihood. Deposits are listed in Appendix B.

predominantly east-dipping and retreating (Aitken et al., 2016). This difference in subduction dynamics may explain the apparent lack of IOCGs within Western Australia.

4.5. Stage 5 – Rodinia assembly and stability (1.29–0.85 Ga)

Globally, the late Mesoproterozoic is the least endowed era, with abundance minima for many ore deposit types, including orogenic gold (Groves et al., 2005a), VHMS (Huston et al., 2010), sedimentary hosted base metals (CD and MVT) (Leach et al., 2010), and IOCGs (Groves et al., 2010). Deposit types that are not strongly dependent on plate-margin processes are still compatible with this era. The interior of Rodinia provides tectonic settings that allow high likelihoods for some ore deposit types (Fig. 12), and western Australia preserves several of these (Fig. 3).

The preserved deposits from this period are associated with the ca. 1085–1040 Ma Giles Event (Evins et al., 2010; Aitken et al., 2013; Maier et al., 2015), the co-eval but widespread Warakurna LIP and Neoproterozoic intraplate basin formation (Walter et al., 1995; Lindsay, 2002). For this stage high-likelihood is suggested for intrusion related gold-copper in the intraplate orogen and continental rift settings. One such mineral system is in the west Musgrave Province, where several hydrothermal copper and gold prospects (E3) are hosted in the volcanic-dominated Bentley Supergroup (Fig. 7). Intraplate orogens include the high- to ultrahigh-temperature Musgrave Orogeny and Albany Fraser Orogeny stage II (Smithies et al., 2011; Spaggiari et al., 2014; Howard et al., 2015), which are not generally favourable for ore-genesis. Similarly aged magmatic suites in the Arunta Orogen and Madura Province, are part of a broad ca. 1150 Ma magmatic province (Aitken and Betts, 2008). These intrusions formed at lower grade, and potential may exist for gold-copper mineralisation in parts of this magmatic province.

High likelihood for Ni-Cu-PGE is indicated for continental rift and LIP settings, of which there are several (Fig. 3). Magmatic Ni-Cu-PGE deposits in the west Musgrave Province include Nebo-Babel (E4), Succoth (E5) and Wingellina (E6). Mineralization is associated with the large layered intrusions of the ca. 1085 Ma to 1075 Ma Giles Suite, and the ca. 1068 Ma Alcurra Dolerite suite.

Warakurna LIP sills and dykes occur widely across WA, but only the Alcurra Dolerite suite possesses known deposits. The west Musgrave province may be preferable for Ni-Cu-PGE mineralisation due to extreme lithospheric thinning from the Musgrave Orogeny (Smithies et al., 2015) causing high levels of magma and heat flux (Maier et al., 2015).

The likelihood of sedimentary-hosted copper deposits is moderate for this stage, however, the ca. 1080 Ma Keeweenaw basin contains several such deposits (e.g White Pine/Presque Isle). The Collier Basin is contemporaneous with the Keweenaw Basin, and possess copper and manganese resources, including the Ilgarari (E1) and Kumarina (E2) deposits. These deposits are shear-zone hosted, but the age and setting of the Collier Basin suggests potential for sedimentary-hosted copper deposits.

4.6. Stage 6 – Rodinia breakup (0.85–0.65 Ga)

The transition from Rodinia to the early stages of Gondwana assembly is associated with an increase in suitable environments for ore genesis. These include long passive and convergent margins and intracontinental rifts. Consequently, this time period sees a resurgence in many ore-deposit types, including orogenic gold (Groves et al., 2005a), VHMS (Huston et al., 2010) and CD-SHBMs (Leach et al., 2010). The global glaciations of the Cryogenian period are also significant, and are temporally associated with both the global peak in sedimentary-hosted copper (Hitzman et al., 2010), and the reappearance of iron-formations (Bekker et al., 2010).

The tectonic setting of Western Australia during this time is dominated by intraplate subsidence and, locally, extension, characterised by the deposition of the Centralian Superbasin across most of central Australia (Walter et al., 1995). The only known large deposit from this basin is sedimentary-hosted copper at Nifty (F1), deposited at ca. 791 $\pm$ 43 Ma (Huston et al., 2005). The Centralian Superbasin contains widespread evaporitic horizons (e.g. Bitter Springs Formation) and suitable conditions for SHBM mineralisation, copper especially, may exist throughout.

Potential exists for magmatic Ni-Cu-PGE associated with the ca. 825 Ma Gairdner (west Musgrave and Madura Provinces) and ca. 750 Ma Mundine Well (Capricorn Orogen) dyke swarms (Fig. 13). These occur as part of large mafic magmatic events, the former broadly contemporaneous with the ca. 825 Ma Jinchuan deposit, although it is unclear if these events involved sufficient magma flux to develop a similar deposit (Song et al., 2011).

4.7. Stage 7 – Gondwana assembly (0.65–0.45 Ga)

Globally, and within eastern Australia, the assembly of Gondwana is associated with several mineralisation styles, including abundant orogenic gold, porphyry Cu-Au and VHMS along the convergent margins (Groves et al., 2005a; Goldfarb et al., 2010; Huston et al., 2010) and stratigraphic hosted base metals (CD and MVT) in rifts, retro-arc basins and passive margin environments (Leach et al., 2010).

Few of these environments are present within Western Australia, which was largely cratonised by this stage (Fig. 14). One potentially prospective environment is the intraplate compressional orogenies, including the King Leopold, Miles, Paterson, Petermann and Alice Springs orogenies.

The King Leopold Orogeny is characterized by a fold-thrust belt at the margins of the Kimberley craton (Tyler and Griffin, 1990), but it is not associated with magmatism or significant mineralization (Lindsay et al., 2015a,b). The Miles Orogeny in the Paterson Orogen involved magmatism, and is prospective for intrusion related gold, hosting the world-class Telfer deposit (G1). The subsequent Paterson Orogeny does not involve magmatism, and is not currently associated with mineralization.

Neither of the Petermann or Alice Springs orogenies is associated with magmatism. Tectonic styles involved large-scale shearing focused on major fault zones, uplift and ductile extrusion of the lower-crust, and extensive fold-thrust belts (Flottmann et al., 2005; Aitken et al., 2009; Raimondo et al., 2009). The nature of these events suggests a cratonic regime overall, and they are not associated with any major mineral system.

The early Cambrian Kalkarindji Large Igneous Province (Glass and Phillips, 2006) involves widespread mafic magmatism over north, west and central Australia, including extensive flood basalts, dykes and sills. There is significant conceptual potential for Noril'sk-style Ni-Cu-PGE mineralization, although no deposits are currently known (Pirajno and Hoatson, 2012).

Some basins of central and western Australia lie adjacent to intraplate orogens during this period, and may preserve prospectivity for MVT-SHBMS. Suitable environments exist within the Canning Basin, including the Devonian reef complexes that host the Lennard Shelf (G2) MVT deposits (Lindsay et al., 2015a).

5. Conclusion

In this review, we have sought to summarise the Proterozoic tectonics of Western Australia, and to put in place frameworks to understand the associated mineral systems in the context of global and regional influences. Using superimposed "tectonic setting likelihood" and "secular likelihood" matrices (Appendix A), we have shown that most (31/37) deposits occur in the "more likely" settings, with a few (6) occurring in "less likely" settings. No deposits are known from "unlikely" settings.

The known mineralization of Western Australia is highly consistent with global empirical paradigms for ore deposit formation. The absences are also revealing, especially where high likelihoods are suggested. In some cases, no deposits are preserved, despite our analysis suggesting relatively high potential. Insufficient exploration may be a partial explanation, but we may also suspect the systematic lack of some key component of the mineral system, including preservation. Prospectivity may be genuinely low in some cases. For example, IOCG formation at ca. 1.6 Ga might have been restricted in Western Australia by unfavourably oriented subduction zones, and Mesoproterozoic orogenic gold and VHMS potential may be limited by poor preservation of the host orogens. Nevertheless, prospectivity may exist in "pockets" that experienced more favourable local conditions and/or better preservation.

As in other parts of the world, Western Australia has the highest endowment associated with the supercontinent Columbia. This endowment is driven by the existence of plate-margin settings from ca. 2.2 Ga to 1.4 Ga (Fig. 3). Globally the lowest endowment is associated with Rodinia, during which time Western Australia was dominated by intraplate tectonic events. Low endowment is offset by the occurrence of rift-related nickel, copper and gold mineralisation events at ca. 1.3 Ga and 1.1 Ga, synchronous with comparable events in Laurentia. The global resurgence of mineralisation systems during Rodinia breakup and Gondwana assembly is not strongly observed within Western Australia, due largely to the predominantly stable intraplate setting.

The strong relationship between mineralisation and supercontinent cycles suggests that the near-neighbours of Western Australia may be similarly endowed. For Gondwana we can expect commonalities with East Antarctica, Northern India, and the terranes of east and southeast Asia rifted off in successive phases of the Tethyan ocean (Metcalfe, 2013). Models of earlier supercontinent configurations are highly variable (Meert, 2014) so these connections are not so well established. Potential near-neighbours within Columbia and Rodinia include East Antarctica, North and South China, North and South India, Siberia, Kalahari and Tarim (Pisarevsky et al., 2003; Li et al., 2008; Zhang et al., 2012; Cawood et al., 2013; Pisarevsky et al., 2014), and these regions may preserve some commonalities with Western Australia.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.gsf.2017.05.008.

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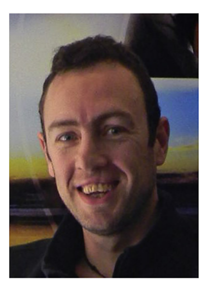


Dr. Alan Aitken has been Goodeve lecturer in geophysics at the UWA since 2012, having previously worked at Monash University, where he also completed his PhD studies in 2008. His research focuses broadly on developing new understandings of the tectonic processes that control the structure of the solid Earth, and in better resolving their importance to society as controlling factors for natural resources and environmental change.

Dr. Sandra Occhipinti completed a BSc Geology at Monash University in 1992. In 1994 she received an MSc for her work in New Caledonia. Following this she worked for the Geological Survey of Western Australia in their Regional Mapping Group. In 2004 she received a PhD from Curtin University. She completed a short post-doc at Curtin University prior to working for Fugro Airborne surveys from 2005 to 2007 as an Interpretation Geoscientist concentrating on West Africa. She worked with AngloGold Ashanti in their Global Greenfields Project Generation team until 2014, before joining the CET, where she works on combing geological, geophysical, geochemical, and geochronological data to define geodynamic models to aid Mineral Systems Analysis.

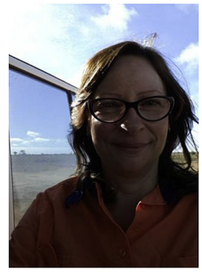
Dr. Mark Lindsay completed his PhD at Monash University and Université Paul Sabatier (Toulouse III) in 2013. Mark is a Research Fellow at the Centre for Exploration Targeting, University of Western Australia and specialises in geophysical and 3D modelling with interest in understanding their interrelated uncertainties. Mark's other research interests includes investigating relationships between geodynamic evolution and mineral systems in Archean and Proterozoic terranes.

Dr. Aurore Joly received her PhD in Geophysics and Geology from the University of Orleans (France, 2007) for a project looking at the evolution of a lithospheric-scale fault in Variscan belt. Her PhD involved 3D forward and inverse geophysical modelling of potential fields data. She then worked five years as a Research Assistant Professor at the University of Western Australia where she applied her expertise to problems associated with mineral exploration, working in Archean granitoid-greenstone terrains & Proterozoic mobile belts. In 2012, Aurore joined St Barbara Pty Ltd as a geophysicist and in 2014, she became a structural geophysicist consultant for Aurora Australis and in 2016 for Resource Potentials.

Dr. Heather Howard completed a PhD at University of Portsmouth (UK) on the geochemistry and petrogenesis of the mafic dykes of Zimbabwe. For more than 14 years she has worked for the Geological Survey of Western Australia, mostly engaged in geoscience mapping and geochemical interpretation of mafic rocks in the west Musgrave Province and Fortescue–Hamersley Basins.

Dr. Simon Johnson completed a PhD in tectonics at St Andrews University in 1998. Since then he has worked in several post-doctoral positions in Australia and Japan before joining the Geological Survey over 10 years ago. The majority of time in the Geological Survey has been spent mapping and understanding the geological history of the Capricorn Orogen.

Dr. Julie Hollis is the Head of the Department of Geology for the Ministry of Mineral Resources, Government of Greenland. Julie has almost 15 years experience working for government geoscience departments and geological surveys in Denmark, Greenland, and Australia. Her expertise is in regional geological mapping of metamorphic terranes, with a focus on metamorphic petrology, structural geology, and geochronology and their application to understanding mineral prospectivity.



Dr. Catherine Spaggiari is the Project Manager for the Albany-Fraser Orogen and Eucla basement projects at the Geological Survey of Western Australia, where she has worked since 2005. Her expertise includes structural geology, geophysics, and tectonics, and coordination of multidisciplinary studies.

Dr. Ian Tyler – FTSE is the Assistant Director Geoscience Mapping at the Geological Survey of Western Australia (GSWA), which he joined joined in 1981 following a PhD at Aston in Birmingham (UK). He has worked throughout WA specialising in the geodynamic evolution of Proterozoic Australia and in the development of its mineral systems. Dr Tyler has been closely involved in the scientific design and implementation of WA's $130 million Exploration Incentive Scheme (EIS), focused on acquisition and rapid publication of high-quality, digital geoscience, deep seismic, geochemical and isotopic datasets relevant to promoting exploration in underexplored areas under cover.

Cam McCuaig is a Principal Geoscientist with BHP Billiton, in their Geoscience Centre of Excellence. Prior to this he was Director of the Centre for Exploration Targeting at the University of Western Australia. Cam has 30 years experience in studying mineral systems, where he has focused on bringing fundamental science into application in the minerals industry. Cam's career has taken him to 41 countries on 6 continents, studying a range of mineral systems from Archaean to Neogene in age.

Mike Dentith is Professor of Geophysics at the University of Western Australia. His research interests are geophysical responses of mineral systems, hard rock petrophysics and regional geophysical studies of mineralised terrains. He is co-author of Geophysics for the Mineral Exploration Geoscientist published by Cambridge University Press.