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VHMS mineralisation at Erayinia in the Eastern Goldfields Superterrane: Geology and geochemistry of the metamorphosed King Zn deposit

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ABSTRACT
Despite having been a target for volcanic-hosted massive sulfide (VHMS) deposits since the 1960s, few resources have been defined in the Archean Yilgarn Craton of Western Australia. Exploration challenges associated with regolith and deep cover exacerbate the already-difficult task of exploring for small, deformed deposits in stratigraphically complex, metamorphosed volcanic terranes. We present results of drill-core logging, petrography, whole-rock geochemistry and portable X-ray Fluorescence data from the King Zn deposit, to help refine mineralogical and geochemical halos associated with VHMS mineralisation in amphibolite-facies greenstone sequences of the Yilgarn Craton. The King Zn deposit (2.15 Mt at 3.47 wt% Zn) occurs as a 1–7 m-thick stratiform lens dominated by iron sulfides, in an overturned, metamorphosed volcanic rock-dominated sequence located ~140 km east of Kalgoorlie. The local stratigraphy is characterised by garnet-amphibolite and strongly banded intermediate to felsic schists, with rare horizons of graphitic schist and talc schist. Massive sulfide mineralisation is characterised by stratiform pyrite–pyrrhotite–sphalerite at the contact between quartz–muscovite schists (‘the footwall dacite’), and banded quartz–biotite and amphibole–garnet schists of the stratigraphic hanging-wall. A zone of pyrite–(sphalerite) and pyrrhotite–pyrite–chalcopyrite vein extends throughout the stratigraphic footwall. Footwall garnet-amphibolites are of sub-alkaline basaltic affinity, with a central zone dominated by chlorite ± magnetite interpreted to represent the Cu-bearing feeder zone. SiO2, CaO, Fe2O3T, MgO and Cu concentrations are highly variable, reflecting quartz–epidote ± chlorite ± magnetite ± sulfide alteration. Hydrothermal alteration in stratigraphically overlying intermediate to felsic rocks is characterised by a mineral assemblage of quartz–muscovite ± chlorite ± albite ± carbonate. Cordierite and anthophyllite are locally significant and indicative of zones of Mg-metasomatism prior to metamorphism. Increases in SiO2, Fe2O3T, pathfinder elements (e.g. As, Sb, Tl), and depletions of Na2O, CaO, Sr and MgO occur in quartz–muscovite schists approaching massive sulfide mineralisation. Within all strata (including the immediate hanging-wall), the following pathfinder elements are strongly correlated with Zn: Ag, As, Au, Bi, Cd, Eu/Eu*, Hg, In, Ni, Pb, Sb, Se and Tl. These geochemical halos resemble less metamorphosed VHMS deposits across the Yilgarn Craton and suggest that although metamorphism leads to element mobility and mineral segregation at the thin-section scale, assay samples of ~20 cm length are sufficient to vector to mineralisation in amphibolite facies greenstone belts. Recognition of minerals such as Mg-chlorite, muscovite, cordierite, anthophyllite, biotite/phlogopite, and abundant garnet are significant, in addition to Al-rich phases (i.e. kyanite, sillimanite, andalusite and/or stauralite) not identified at King. Chemographic diagrams may be used to identify and distinguish different alteration trends, along with several alteration indices (e.g. Alteration Index, Carbonate–Chlorite–Pyrite Index, Silicification Index) and the abundance of normative corundum and quartz.

Introduction
For the last four decades, exploration for volcanic-hosted massive sulfide (VHMS) mineralisation in the Archean Yilgarn Craton of Western Australia (Figure 1) has been hampered by a perceived lack of prospectivity and difficult exploration conditions. The latter include deep and transported overburden, a paucity of outcrop, high strain, and saline groundwaters (Hollis et al., 2015; McConachy, McInnes, & Carr, 2004; Vearncombe, 2010; Yeats, 2007). In many greenstone belts, the proximity of supracrustal rocks to late-stage granites, which comprise much of the craton, adds further complications. Metamorphic grade varies...
across the craton from greenschist to granulite facies, generally being higher closer to greenstone margins, and within narrower greenstone belts (e.g. Swager, 1997; Witt, 1991; Witt & Hagemann, 2012).

Few VHMS deposits have been identified in greenstone sequences metamorphosed to relatively high grade in the Yilgarn Craton (reviewed in Hollis et al., 2017a), as relatively simple primary alteration assemblages are commonly overprinted and obscured, with host rocks now comprising mineralogically complex banded schist or gneiss. For example, at Kingsley (the Wheatley prospect, South West Terrane; Figure 1), massive sulfide mineralisation is hosted at a transition between quartz–feldspar–biotite gneiss and hornblende–plagioclase–biotite–quartz ± garnet-amphibolite, marking a shift from felsic to mafic volcanism (Hassan, 2017a; Yeats, 2007). Sodium depletion in felsic gneisses underneath mineralisation and the Al-rich minerals sillimanite, staurolite, kyanite and garnet provide evidence for a metamorphosed hydrothermal system (Hassan, 2017a; Yeats, 2007). In the eastern half of the Quinns district (Murchison Domain, Youanmi Terrane; Figure 1), schistose rhyolite contains locally abundant and coarse-grained andalusite ± kyanite ± garnet where associated with VHMS mineralisation (Duuring, Hassan, Zelic, & Gessner, 2016; Hassan, 2017b). The recognition of garnet and staurolite porphyroblasts for 30 m above and below the Hollandaire deposit (Murchison Domain, Youanmi Terrane; Figure 1) was also significant for VHMS exploration in the area (Hayman et al., 2015a).

Despite the increased difficulty of discovery, the metamorphism and deformation of VHMS deposits may bring economic benefits. These can include the significant upgrading and redistribution of gold during metamorphism (e.g. Boliden deposit, Sweden; Wagner, Klend, Wenzel, & Mattsson, 2007), and the thickening of massive sulfide ores in hinge zones of folds (Dusel-Bacon, 2012). We present results of drill-core logging, petrography, whole-rock geochemistry and portable X-ray fluorescence (pXRF) data from the King Zn VHMS deposit in the Erayinia region of the southern Kurnalpi Terrane (Edjudina Domain; Figure 1). We show that the mineralogical and geochemical signatures of the magmatic, hydrothermal and metamorphic events can be resolved. From these inferences, we discuss features that may be used to identify VHMS deposits that have
been metamorphosed at amphibolite facies in the Yilgarn Craton.

**Geological setting**

The Yilgarn Craton has historically been divided into a series of terranes based on distinct lithological associations, geochemistry and ages of volcanism (Cassidy et al., 2006; Gee, Baxter, Wilde, & Williams, 1981; Myers, 1990). The western half of the Yilgarn Craton comprises the Narryer, South West and Youanmi terranes (Figure 1). East of the Ida Fault, the Eastern Goldfields Superterrane (EGS) can be divided into the Kalgoorlie, Kurnalpi, Burtville and Yamarna terranes (Pawley et al., 2012; Figure 1). The geology of the Yilgarn Craton with respect to VHMS mineralisation has recently been discussed by Hollis et al. (2015, 2017a). Here we summarise the regional geology of the Kalgoorlie and Kurnalpi terranes (Figures 1 and 2).

The geology of the Kalgoorlie Terrane is broadly divisible into the lower 2720–2690 Ma mafic–ultramafic Kambalda Sequence (Beresford, Stone, Cas, Lahaye, & Jane, 2005) and the overlying 2690–2660 Ma Kalgoorlie Sequence (Krapeč & Hand, 2008) (Figure 2). At least two magmatic cycles, interpreted as plume-related, are recognised in the lower sequence (Hayman et al., 2015b). The overlying 2690–2660 Ma Kalgoorlie Sequence comprises a >3 km-thick package of volcaniclastic rocks, felsic volcanic rocks, and mafic intrusive complexes with minor mafic volcanic rocks (Squire et al., 2010; Figure 2). Late doming and extension associated with the emplacement of a widespread tonalite–trondjhemite–granodiorite (TTG) suite produced the late clastic basins of the Eastern Goldfields (Wyche et al., 2013; Figure 2).

Broadly coeval with the Kambalda Sequence of the Kalgoorlie Terrane, the Kurnalpi and Minerie sequences of the Kurnalpi Terrane are represented by a more intermediate package of rocks (Figure 2). Although some workers have attributed the Kurnalpi andesites to an Archean arc (and thus the Kalgoorlie Terrane to a backarc; e.g. Czarnota et al., 2010), they are also geochemically consistent with the fractionation of plume-related tholeiitic basalts, coupled with their contamination by contemporaneous partial melts of pre-existing continental crust (Barnes & Van Kranendonk, 2014). Between 2692 and 2680 Ma, volcanic centres in the Kurnalpi Terrane (Gindalbie Domain and further south; Figure 1) are associated with largely bimodal (basalt–rhyolite) volcanic and associated sedimentary rocks, although some contain significant volumes of andesites (Figure 2). These felsic rocks are significantly enriched in the high field strength elements (HFSE) and heavy rare earth elements (HREE) (Barley, Brown, Krapeč, & Kositcin, 2008; Brown, Barley, Krapeč, & Cas, 2002; Hollis et al., 2015) and are diagnostic of shallow crustal melting (Hart, Gibson, & Lesher, 2004; Lesher, Goodwin, Campbell, & Gorton, 1986; Piercey, Paradis, Murphy, & Mortensen, 2001). This region of HFSE-enriched felsic volcanic rocks and broadly coeval HFSE-enriched granitic intrusions (Hollis et al., 2015) coincides with an area of juvenile crust revealed through regional Sm–Nd (granite; Figure 3) and Pb isotope (galena) variations (Huston, Champion, & Cassidy, 2014). Interpreted as a paleo-rift zone, where juvenile material was added to the crust, similar isotopic features have also been recognised in the Youanmi Terrane (i.e. Cue Zone) and Abitibi-Wawa subprovince of Canada where they are associated with VHMS mineralisation (Huston et al., 2014). To date, only three VHMS deposits have been mined in the Eastern Goldfields...
Superterrane—all from the ca 2690 Ma Teutonic Bore volcanic complex (Belford, Davidson, McPhie, & Large, 2015; Hallberg & Thompson, 1985; Figure 3). A significant resource of Ag-rich VHMS mineralisation has also been recognised in the Kalgoorlie Terrane at Nimbus (Figure 3), interpreted to represent a shallow-water and low-temperature deposit formed on the margin of the Kurnalpi rift zone at ca 2705 Ma (Hollis et al., 2017a).

Regional geology of Erayinia

The regional geology of the Erayinia area in the southern Kurnalpi Terrane is detailed in the 1:100 000 GSWA explanatory notes (Jones, 2007). Two major faults (Claypan and Roe Hills) divide the area into three domains—Edjudina, Murrin and Menangina (Figure 4). As the Edjudina Domain at King is the focus of this paper, the other two domains will not be discussed. An account of VHMS mineralisation in the Murrin Domain (Figure 4) will be presented elsewhere.

The Edjudina Domain across its ~300 km length (Figure 1) is dominated by several basaltic to rhyolitic volcanic complexes, and laterally extensive belts of intermediate schist predominantly derived from andesitic precursors (Swager, 1995, 1997). Prominent, although volumetrically minor, marker beds of banded iron formations (BIF), chert and fine-grained metasedimentary rocks cap the aforementioned sequence, which are intruded by extensive dolerite sills (Swager, 1995, 1997). A narrow eastern belt of thin basalt, which contains komatiite layers was also recognised. Existing U–Pb zircon ages from the southern half of the Edjudina Domain are limited to: (1) 2708 ± 6 Ma from a fragmental metadacite porphyry in a felsic sequence associated with calc-alkaline rocks ~100 km N of King (Nelson, 1995); (2) 2698 ± 10 Ma from a metatonalite intrusion also ~100 km N of King (Nelson, 1996); and (3) 2680 ± 4 Ma from a granite gneiss at Coonana Hill ~30 km NE of King (Wingate, Lu, Kirkland, & Spaggiari, 2016). The distribution of komatiite and BIF within the southern Eastern

Figure 3. Regional Nd isotope variations of the Yilgarn Craton (modified after Wyche et al., 2013). The position of significant VHMS occurrences associated with the Kurnalpi paleo-rift zone (highlighted by younger depleted mantle model ages) is indicated by red stars.
Goldfields, along with all current U–Pb zircon ages from the region, is shown in Figure 5.

Jones (2007) provides a more local summary of the geology at Erayinia east of the Claypan Fault (Figure 4). According to Jones (2007), greenstone sequences contain interlayered mafic and felsic schists, ferruginous chert bands and silicified black shales that define tight folds on aeromagnetic images. Further east, along the eastern margin of Erayinia, thin units of meta-ultramafic rocks (komatiite?) and metabasalt are interlayered with metasedimentary rocks (Figure 4). The mapped meta-ultramafic rocks are preserved as deeply weathered talc–chlorite–carbonate schists ~17 km SE of King (Figure 4; Jones, 2007). Together with the presence of a large rubbly outcrop of Fe-rich chert ~10 km N of King, which is similar in appearance to BIF (Jones, 2007), this may suggest the local stratigraphy is >2.7 Ga in age and belongs to the Minerie or Kurnalpi sequence (Figure 2). Such an age is also consistent with the presence of 10–50 m thick sequences of talc-sericite-quartz schist in the King stratigraphy, which may represent hydrothermally altered and metamorphosed ultramafic rocks. The Gindalbie age (2680 ± 4 Ma) from a ‘granite gneiss’ at Coonana Hill ~30 km NE of King (Wingate et al., 2016; Figure 5) may belong to a similar sequence to the ‘schist derived from granite rock’ mapped by Jones (2007) in Figure 4. Unfortunately, our attempted U–Pb dating of the King stratigraphy was unsuccessful owing to a paucity of zircons recovered from footwall quartz–muscovite schists.

Regional deformation of the Erayinia region is complex and typically involved an early extensional event (D1), followed by: D1 compression involving thrusting and recumbent folding (F1); D2 ENE–WSW crustal shortening, producing major upright folding (F2: 2675–2657 Ma); D3 sinistral movement and associated folding on NNW-trending regional strike slip faults; and D4 overprinting with oblique reverse movements on the same structures (Jones, 2007).

Peak metamorphism across the Eastern Goldfields is most intense (upper amphibolite facies) surrounding large granitoid bodies that were emplaced at 2660–2640 Ma, broadly contemporaneous with D2 deformation (Nelson, 1997; Swager, Goleby, Drummond, Rattenbury, & Williams, 1997; Witt, 1991). Away from these granitoids, porphyroblasts of biotite and andalusite grew over and across the vertical regional foliation indicating the relatively late timing of peak regional metamorphic conditions (Swager, 1997). Lower-grade zones of greenschist facies
metamorphism are found in the central parts of greenstone belts (Jones, 2007). A marked increase in metamorphic grade was noted by Jones (2007) across the Claypan Fault (Figure 4), from relatively undeformed greenschist facies felsic volcaniclastic rocks and basalt in the west, to muscovite schist, chlorite–muscovite schist and biotite–garnet schist east of the fault.

**King deposit stratigraphy**

The King Zn deposit (~2.146 Mt at 3.47 wt% Zn, non-compliant at 1 wt% cut off) occurs in an overturned and east-dipping volcanic-dominated sequence (Figure 6) located approximately 140 km east of Kalgoorlie (Figure 1) and 36 km south of the Trans Australian Railway. Although the area had previously been explored for uranium and gold, base-metal mineralisation was first targeted during the 1990s by Sons of Gwalia. Following geological mapping, ground magnetometry and surface TEM geophysics, a conductor was recognised as coincident with a magnetic anomaly. Further soil sampling and Reverse Circulation (RC) drilling led to the interception of narrow massive sulfide layers at King (formerly called Calliope). The most extensive exploration activity was undertaken by ABM Resources.
from 2005 to 2012 as the manager of a joint venture with Hawthorn Resources Ltd (detailed in Podmore & James, 2016). Subsequent diamond, RC and Rotary Air Blast drilling by ABM defined the current size of the King deposit (Figure 6a, b). More recently, a soil and rock-chip sampling program, and VTEM (Versatile Time Domain EM) geophysical survey, was undertaken by Black Raven Mining (2012–2017) over the extended licence areas.

Our current interpretation is that the volcanic stratigraphy at King is overturned and dipping to the east (Figure 6c). This is based on metal zonation in the deposit, and the distribution and intensity of logged hydrothermal alteration assemblages. An intensely chloritised zone of discordant alteration with abundant chalcopyrite and Fe sulfides lies above a sheet-like body of massive Fe–Zn sulfide (Figure 6d), the opposite to most VHMS systems.

Figure 6. (a) Drill-hole map of the King Zn–(Cu) deposit. (b) Composite longitudinal section through the deposit highlighting the two Zn-rich ore lenses (after ABM Resources NL, 2009). (c) Cross-section showing the interpreted main geological units discussed in the text. (d) Cross-section showing the main alteration minerals present and base-metal mineralisation. Dashed lines reflect the interpreted geology illustrated in Figure 6c.
Graded beds were also noted by ABM geologists from drill-holes EC120D and EC116D (ABM Resources NL, 2008) consistent with our interpretation, although these have not been verified since. Possible graded bedding from hole EC056D is shown in Figure 7l. An overturned stratigraphy is also consistent with Swager’s (1995, 1997) description of rocks from the Edjudina Domain—namely basaltic to felsic volcanic complexes, overlain by fine-grained sedimentary rocks, chert and BIF intruded by mafic sills—and also a recent study from King North (Kelly, 2018; Figure 4).

Photographs of the main lithologies and styles of mineralisation present in diamond drill-core are shown in Figure 7.

Figure 7. Representative photographs of the main lithologies observed and styles of hydrothermal alteration present at King. (a, b) Variably banded and sheared footwall garnet-amphibolite. (c) Intensely chloritised zone of footwall amphibolite containing disseminated magnetite. (d) Anthophyllite-bearing schist from the mixed footwall sequence. (e, f) Folded and banded schist from the mixed footwall sequence with individual layers composed almost entirely of quartz, muscovite and epidote. (g) Albite-rich schists from the mixed footwall sequence. (h) Intensely silicified footwall felsic rocks (quartz–muscovite schist). (i) Finely banded quartz–biotite and amphibole±garnet schists from the stratigraphic hanging-wall of the deposit. Note the variation in rock types and alteration. (j) Finely banded silicified hanging-wall schists. (k) Polymict volcanic breccia with clasts of surrounding lithologies. (l) Possible grading in drill-hole EC056D (hanging-wall strata), with coarse bases and schists fining downhole. (m) Early quartz–feldspar porphyry sill intruding the King deposit stratigraphy (sample GK024; Figure 6c, labelled 1). (n) Late unaltered quartz–feldspar porphyry sill intruding the King deposit stratigraphy (Figure 6c, labelled 2). (o) Basaltic dyke most likely from the Paleoproterozoic Widgiemooltha Dyke Suite cutting the footwall garnet-amphibolite. Varioles are commonly present near upper and lower contacts.
Figures 7 and 8. The stratigraphy at the King deposit from interpreted stratigraphic footwall to hanging-wall, assuming an overturned stratigraphy, is shown in Figure 6c.

Footwall garnet-amphibolite

A thick (>300 m) sequence of foliated garnet-amphibolite or hornblende–garnet–quartz schist (Figures 7ab and 9a) occurs in the deep stratigraphic footwall of the King deposit, with the top contact now ~100–150 m above mineralisation (Figure 6c). The groundmass is dominated by fine granulose green hornblende with interstitial fine anhedral quartz, minor epidote and carbonate (Figure 9a). Garnet porphyroblasts contain quartz and hornblende inclusions. A general anastomosing schistosity (Figure 7b) is paralleled by the granulose hornblende texture. Local zones with abundant ragged and acicular actinolite (to ~3 mm in drill-core) also occur. Towards the centre of the King deposit, a zone characterised by abundant chlorite is present (Figures 6d and 9d). This is best observed in drillholes EC116D and EC143D where fine magnetite crystals are disseminated throughout the core in close association with chalcopyrite ± pyrrhotite ± pyrite blebs and stringers (Figures 8a, b and 9b, c). Contacts are gradational with surrounding garnet-amphibolites, with the change in rock type reflecting an increased abundance of chlorite ± magnetite to hornblende–garnet–quartz.

The thick sequence of garnet-amphibolite is interpreted to represent a sheared and metamorphosed sequence of mafic rocks. It is unclear, owing to the strong banding and recrystallisation, whether these represent metamorphosed coherent mafic flows, volcaniclastic rocks or thick basaltic sills. Primary volcanic textures such as pillows, varioles, chilled margins and peperite are not preserved. Similar mafic lithologies have been mapped by Jones (2007) along strike to the north of the King deposit (weakly foliated amphibolite; Figure 4). Quartz and epidote altered mafic
Figure 9. Photomicrographs, SEM images and chemical maps for representative samples from the King stratigraphy. (a) Footwall garnet-amphibolite with disseminated sulfides. (b) Reflected light image of sulfide and oxide phases present within footwall garnet-amphibolites. (c) Chemical map of the area in Figure 9b (denoted by a white box). (d) Intensely chloritised zone of garnet-amphibolites. (e) Quartz–hornblende schist from the mixed footwall sequence. (f–h) Anthophyllite bearing quartz–biotite–chlorite–albite–epidote schist from the mixed footwall sequence. (i, j) Quartz–muscovite schist from the immediate footwall of the King deposit. (k) Coarse euhedral pyrite in quartz–muscovite schist, with interstitial sphalerite. (l) Massive sulfide with sphalerite replacing pyrite and large milled clasts of surrounding quartz–muscovite schist. (m, n) Massive sulfides containing garnet porphyroblasts retrograded to chlorite. (o–r) Petrographic and SEM images of hanging-wall mafic (o, r) and felsic (p, q) strata. Drill-hole numbers and sample depths are indicated by the format 116/425 m. (a, f) Plane-polarised light; (d, e, i, j, o–q) Cross-polarised light; (g, k, m, r) SEM images; and (c, h, n) SEM composite chemical maps. Chemical mapping was completed using a Hitachi TM3030Plus Tabletop Scanning Electron Microscope at University College Dublin, Ireland. Maps were completed over 2–3 h each using a pixel dwell time of 800 μs, resolution of 1024 and process time of 4 s. Composite colour maps were produced by merging element concentration maps of interest using the Oxford Instruments Aztec One (v. 3.2) software.
volcanic rocks (greenschist facies), which are geochemically similar to those described here, have also been recently drilled at King North along strike (Kelly, 2018; Figure 4). The zone of intense chlorite-magnetite with Cu-Fe sulfides is interpreted to represent the feeder zone to massive sulfide mineralisation that was enriched in Mg prior to metamorphism.

**Mixed footwall sequence**

Stratigraphically overlying the garnet-amphibolite is a ~30 to 130 m-thick mixed sequence of intensely altered, intermediate to felsic schist. Rare units (<15 m thick) resembling the aforementioned footwall garnet-amphibolite also occur. Rocks of the mixed footwall sequence are highly variable in their mineralogy and are strongly banded and folded (Figure 7d–g). More leucocratic (intermediate to felsic) lithologies are dominated by a combination of quartz, chlorite and carbonate with lesser hornblende, biotite and epidote (Figure 9e–h). Where present, biotite parallels the schistosity and is commonly retrogressed to chlorite. Leucocxene, zircon and titanite are present as accessory phases. Zones rich in albite and/or muscovite also occur. In the rare mafic lithologies, the metamorphic matrix is dominated by hornblende with minor epidote in darker bands, and quartz–epidote–chlorite in paler bands.

Throughout each of the drill-holes logged at the King deposit (Figure 6a), a distinct zone of intense brown and green banding is common (Figure 7d). This occurs at depths anywhere from ~50 to 150 m in the footwall to massive sulfide mineralisation and varies in thickness from a few metres (EC114D) to over a hundred metres (EC144D). This lithology is characterised by quartz, anthophyllite, clinzoisite and biotite (intergrown with anthophyllite and replaced by chlorite) (Figure 9f–h). A 20 m wide zone of abundant coarse completely sericitised cordierite (?) porphyroblasts occurs in the anthophyllite-bearing schists in drill-holes EC118D, EC153D and EC144D (Figure 6a).

The mixed footwall sequence is interpreted to represent a package of metamorphosed intermediate to felsic volcaniclastic rocks, with rare mafic sills/lava flows (now garnet-amphibolite) and thin beds of deep-marine argillaceous sediments (typically <2 m thick; preserved as graphitic schist). Rare examples of lapilli tuff have been described from this sequence, with relict quartz clasts apparent in thin-section. The zone rich in anthophyllite is interpreted to reflect Mg-metasomatism prior to metamorphism in the intermediate to felsic lithologies. A 10 to 50 m thick, often fault-bound, package of talc-sericite-quartz schist with clots of specular hematite may represent a sequence of hydrothermally altered and metamorphosed ultramafic rocks.

**Quartz–muscovite schist (footwall dacite)**

A ~50 to 90 m-thick sequence of leucocratic and variably banded quartz–muscovite schist of dacitic composition comprises the immediate stratigraphic footwall to massive sulfide mineralisation at King (Figures 6c and 7h). In some instances, coherent and weakly altered units occur in close proximity to mineralisation, surrounded by intensely altered and sheared lithologies. Quartz–muscovite schists are dominated by fine granoblastic quartz with interstitial platy muscovite defining the schistosity (Figure 9i, j), and minor epidote. Locally, Mg-rich cordierite can be significant (≤5 vol%) as aggregates and crystals throughout the matrix and is commonly replaced by sericite and associated Mg-chlorite. Bands of sericitised plagioclase occur in the matrix of some samples. Sulfides, tourmaline, hornblende, leucoxene and zircon are present as accessory phases (Figure 9k).

Garnets are rare, but small (<2 mm) pink to red porphyroblasts are disseminated throughout most units logged. Directly under massive sulfides (Figure 9l), the quartz–muscovite schists are intensely silicified in hand specimen. With depth, an increase in muscovite, chlorite and albite is clear in drill-core (Figure 6c). Contacts between different styles of alteration are gradational. Where present, pyrite and sphalerite occur as stringers and disseminated throughout the host stratigraphy (Figures 8c and 9k).

The thick sequence of quartz–muscovite schist is interpreted to represent a mixed, hydrothermally altered and metamorphosed sequence of dacitic volcaniclastic rocks and more coherent volcanic lithologies (either representing flows or high-level intrusions). No quartz or feldspar phenocrysts were observed. All rocks examined in thin-section are strongly recrystallised and show evidence of shearing.

**Mixed hanging-wall sequence**

The immediate hanging-wall of the King deposit is dominated by finely banded (mm to cm scale) schists of mafic to felsic composition (Figure 7l), grouped together here as quartz–biotite and amphibole±garnet schists. Banding reflects the varying abundance of fine to medium granoblastic quartz (with lesser biotite) to tremolite/actinolite±garnet (Figure 9o, p). Garnet can be retrogressed to fibrous chlorite aggregates with quartz. Calcite is present throughout the matrix, as well as in veinlets and vugs (Figure 9q, r). Magnetite is disseminated (3–5 vol%) throughout the matrix of grunerite-bearing banded schists (the ‘hanging-wall BIF’) directly overlying massive sulfides (Figure 6). In the deeper sections of the deposit where magnetite has not been replaced by secondary Fe-oxides, a very strong magnetic signature persists for ~1 to 4 m into the stratigraphic hanging-wall. This zone is typically more magnetic than the pyrrhotite–magnetite-bearing chloritic feeder zone, but the intensity of both varies significantly from hole to hole. Pyrite stringers, which are abundant close to massive sulfides and are strongly recrystallised, are both parallel and cut metamorphic banding at high angles (Figure 8g). The most convincing example of grading, shown in Figure 7l, is consistent with an overturned stratigraphy.
Thick horizons of graphitic schist, quartz-eye tuffs (e.g. EC043D), pyrite-bearing polymict volcanic breccias (Figure 7k) and rare, coherent carbonate-altered rocks of mafic composition (herein termed the hanging-wall amphibolites) are also present in the stratigraphic hanging-wall to mineralisation. The hanging-wall amphibolites (~3 m thick) are dominated by amphibole and quartz, with carbonate alteration and relict clinopyroxene. Garnets can be present, but not in every drill-hole. Finely banded chert-like rocks were noted at ~385 m depth in drill-hole EC056D (Figure 7j). The polymict volcanic breccias (EC056D ~382 m) are intensely brecciated, quartz-veined, contain clasts up to 4 cm of surrounding lithologies (e.g. layered chert, banded schist, amphibolite), and thin strings of magnetite.

The mixed hanging-wall sequence is interpreted to represent a sequence of metamorphosed interbedded volcanic/volcaniclastic rocks of varying composition, with interbedded fine-grained, deep-marine sedimentary rocks. The hanging-wall amphibolites may represent very thin lava flows or coeval basaltic sills (e.g. Swager, 1997).

**Horizons of graphitic schist**

Thin (0.4–2 m) horizons of graphitic schist have been identified throughout the King stratigraphy in both the interpreted footwall (EC086D 303 m) and hanging-wall (EC143D ~505 m) to massive sulfide mineralisation. Similar lithologies were also noted as deformed fragments within the massive sulfide zone of drill-hole EC116D, where they are intensely chloritised and in some sections appear to have been replaced by sulfides. The horizons of graphitic schist are always intensely fractured, strongly sheared, and can be intermittently banded with surrounding lithologies (e.g. garnet-amphibolite, quartz–muscovite schists). In most instances, fault gouges are closely associated with the graphitic schists, indicative of thrusting in the stratigraphy. The graphitic schists most likely represent metamorphosed deep-marine argillaceous sediments precipitated under anoxic conditions.

**Quartz–feldspar phryic intrusive rocks**

The King stratigraphy has been intruded by at least two generations of quartz–feldspar porphyry sills that broadly parallel bedding (Figure 6). The earlier set appears to be broadly coeval with the volcanic stratigraphy and are ~0.7 to 1.5 m thick with sharp margins (e.g. EC056D 309 m, EC116D 387 m). They exhibit a similar mineralogy (quartz–muscovite) to the footwall felsic rocks they intrude, contain disseminated sulfides and have a strong foliation, which parallels surrounding strata (Figures 6c, labelled 1 and 7m).

A presumably younger set of thinner (5–30 cm) quartz–feldspar phryic sills intrude the hanging-wall to massive sulfide mineralisation in drill-hole EC056D (~363 m; Figure 6c, labelled 2). This suite is less foliated (Figure 7n) and resembles that of the ERAinia NW area closely associated with late high-Ca granitoid intrusions of the eastern Murrin Domain. Sharp unchilled margins are orientated parallel to banding in surrounding schists.

**Late basaltic dykes**

Late basaltic dykes cross-cut the stratigraphy and are undeformed. These rocks are typically ~0.5 to 2.5 m thick, coarsen to doleritic centres, and display chilled margins and varioles (Figure 7o). They most likely belong to the Paleoproterozoic Widgiemooltha Dyke Suite (Figure 6). The suite is clearly visible in regional magnetics and intrudes the area in predominantly E–W and NNE–SSW orientations (Figure 4).

**Sulfide mineralisation at King**

Sulfide mineralisation at King occurs predominantly as a stratiform, ~1 to 7 m-thick, sheet-like body of massive pyrite–pyrrhotite with subordinate sphalerite, at the contact between intensely silicified dacite (footwall quartz–muscovite schist) and banded quartz–biotite and amphibole ± garnet schist (Figure 6c). This zone of stratiform massive sulfide mineralisation dips at 45–70° eastwards, has a confirmed depth of at least 400 m, and has been drilled across a strike length of ~600 m (Figure 6a). Diamond drilling is restricted to the central 450 m (Figure 6a). Two small, high-grade lenses of Zn mineralisation have been recognised separated by a central zone (150–200 m long) with lower Zn grades (Figure 6b). The best intercept is 5 m at 10.6 wt% Zn in drill-hole EC116D. There has been sporadic analysis for gold in both massive sulfides and the feeder zone. Significant intercepts include 5 m at 0.6 g/t Au (EC046D) and 5.9 m at 0.3 g/t Au (EC031D) (Figure 6b). Stratigraphically underlying the stratiform massive sulfides, a zone of discordant vein and disseminated sulfides (from pyrite–sphalerite to pyrrhotite–chalcopyrite–pyrite; Figure 8a, b) extends throughout the underlying strata (Figure 6d). It is important to note that all sulfide assemblages show evidence for recrystallisation.

Within the massive sulfides, two broad styles of mineralisation can be defined: a lower zone characterised by fine-to coarse-grained subhedral pyrite with replacive interstitial red/brown sphalerite (Figure 8d) and a stratigraphically overlying zone dominated by iron sulfides (pyrite and/or pyrrhotite) with large milled clasts of surrounding lithologies (Figures 8e and 9l–n). In the stratigraphically lower Zn-rich zone, abundant fine- to coarse-grained subhedral pyrite is replaced by sphalerite (Figures 8d and 9l). Anhedral quartz and Fe-chlorite are interstitial to sulfide phases. Pyrrhotite is concentrated locally in the matrix. Galena is rare and is present as rims to, and inclusions in, pyrite. Tetrahedrite locally replaces galena and exhibits simple intergrowths with sphalerite.

In the overlying Fe-rich zone, pyrite and/or pyrrhotite are typically the dominant sulfide phase with subordinate sphalerite and rare galena. Chalcopyrite inclusions occur in
pyrrhotite. Siliceous clasts of varying size are present in the sulfide matrix. These are well rounded and represented by quartz–muscovite schist derived from the underlying footwall, or schist from the stratigraphic hanging-wall (Figure 9m, n). Garnet in the hanging-wall schist fragments is retrogressed to chlorite (Figure 9n). In drill-hole EC116D, abundant fragments of chloritised and deformed graphitic schist are within the massive sulfides.

Silicified felsic footwall rocks immediately underlying massive sulfides contain veinlets of pyrite–sphalerite, which
become more sphalerite poor with depth. These are commonly strongly sheared, with trails of coarse euhedral pyrite orientated parallel to metamorphic banding (Figure 8c), and the contact with overlying massive sulfides (Figure 8d). When present, sphalerite occurs interstitially to euhedral pyrite (Figure 9k), with both phases cut by veinlets of galena.

In the chlorite-rich zone of garnet-amphibolite (Figure 6d), chalcopyrite is most common as blebs and stringers, along with veinlets and individual crystals of pyrrhotite and pyrite (e.g. EC116D; Figure 8a, b). Sphalerite crystals are commonly strongly deformed and may be intergrown with both chalcopyrite and pyrrhotite. Ilmenite (FeTiO₃) occurs as exsolution lamellae in the coarse magnetite grains, and as individual crystals in pyrrhotite (Figure 9b, c). Pentlandite ([Fe,Ni]₉S₈) is rare and is intergrown with pyrrhotite. Chalcopyrite is also intergrown with pyrrhotite and fills fractures in magnetite grains (Figure 9c). Drill-core logging also revealed that secondary Cu minerals (predominantly malachite) are present in the uppermost sections of the King deposit, most likely remobilised from the underlying Cu-bearing chloritic stockwork.

The immediate hanging-wall above massive sulfides can contain abundant stringers of coarse euhedral pyrite (Figure 8g) orientated both along the main foliation and cross-cutting brecciated hanging-wall lithologies.

**Geochemistry**

**Methods**

**Whole-rock lithogeochemistry**

A total of 23 samples of diamond drill core from the King stratigraphy (drill-holes EC116D, EC031D, EC056D; Figure 6c) were analysed for whole-rock geochemistry at ALS Laboratories, Perth, Australia. Major element concentrations were determined by four acid digestion and ICP-OES finish on fused glass beads. Trace element, HFSE and REE concentrations were determined by lithium borate fusion and ICP-MS finish. Base metals (e.g. Cu, Pb, Zn, Ni) and trace metals (e.g. As, Sb, Ti, Bi) were analysed by multi-acid digestion, followed by ICP-OES and ICP-AES, respectively. Carbon and S concentrations were determined by total combustion using a Carbon-Sulfur Analyser, and LOI using a robotic thermo-gravimetric system. Gold, Pt and Pd concentrations were analysed by fire assay and ICP-OES.

Accuracy (%RD) was monitored using laboratory blind, mineralised and unmineralised international standards (e.g. OREAS-24b—granodiorite; OREAS-620—Golden Grove ore). Precision (%RSD) was monitored by repeat analysis of submitted standard OREAS-24b (granodiorite). Both precision and accuracy are considered excellent to good after Jenner (1996; i.e. within ±10% RSD and <10% RD) for the majority of elements from both datasets. W, Li, Sn and Mo data were discarded owing to poorer accuracy and/or precision than the other elements (consistently >10% RD to international standards). Thallium data were retained owing to excellent precision (<1% RSD), but absolute values here should be treated with caution as accuracy was poor (>30% RD). Whole-rock geochemistry results are presented in the Supplementary papers (Table S1) and plotted in Figures 10 to 13.

**Portable X-ray fluorescence geochemistry**

The above whole-rock geochemical data from the King deposit are complemented by ~620 pXRF measurements on diamond drill-core (5 holes). Portable XRF measurements were made every 0.5 to 2 m of core (dependent on hole length) using an Olympus InnoveX Systems Delta 2012 series model between March and May 2015. The counting time was 60 s per analysis in soil mode. Several studies using international reference materials have shown pXRF data to be precise for a number of major and trace elements (e.g. Piercey & Devine, 2014). Although the accuracy of pXRF data ranges widely from excellent (<7% RD) to
poor (±20% RD), and commonly needs correcting (e.g. Fisher et al., 2014; Le Valliant, Barnes, Fisher, Fiorentini, & Caruso, 2014), downhole profiles replicate the geometry of those obtained from conventional analyses (Piercey & Devine, 2014). Such data are fit for purpose and useful for enhancing downhole geochemical trends obtained by conventional methods but should not be used as a substitute for high-quality lithogeochemistry (Piercey & Devine, 2014). pXRF data were corrected using 11 standards from OREAS (OREAS-22d, 24b, 24c, 36, 38, 70b, 76b, 291, 921, 935, 991) for the following elements: As, Cr, Cu, Fe, Mn, Ni, Pb, Rb, Sr, Ti, V, Y, Zr and Zn. These standards cover a wide range of concentrations for each element (e.g. 38 ppm to 12.4 wt% Cu, 4.45–23.6 wt% Fe). Calibration equations were obtained by plotting certified concentrations against obtained pXRF values for each element. Only standards that returned pXRF values above the limit of determination (LOD: 3x detection) were used in each equation. This process was carried out separately for each drill-hole. As an increase in pXRF machine internal temperature (and consequently air pressure) is known to cause instrument drift over time (owing to peak positions migrating; Gazley & Fisher, 2014), standard OREAS-24b was analysed every 15–20 spot analyses (total n = 71 for five drill-holes). Apart from single point anomalies, instrument drift was found to be negligible and non-systematic.

Calibration equations used to correct pXRF data are provided in the Supplementary papers (Table S2) along with Figure 12.

Figure 12. Mobile element geochemistry of samples analysed from King. The Box Plot (bottom left) uses both the Alteration Index (AI) of Ishikawa et al. (1976) and the Carbonate-Chlorite-Pyrite Index (CCPI) of Large et al. (2001a) to show common trends associated with hydrothermal alteration. AI = 100 × (K₂O + MgO)/(K₂O + MgO + Na₂O + CaO); CCPI = 100 × (MgO + FeO)/(MgO + FeO + Na₂O + K₂O).
$R^2$ values, which were generally excellent (most >0.98) apart from for Cr and V (that were rarely above LOD). Slight offsets between corrected pXRF and lithogeochemical datasets are to be expected, owing to the effect of spot analysis (~10 mm diameter) on heterogeneous drill-core (Gazley & Fisher, 2014), and attenuations of elements by the plastic bags in which standards were analysed (see Fisher et al., 2014). That said, these combined effects appear to be minimal here for the elements of interest. Our corrected pXRF data closely follow data obtained by conventional lithogeochemical methods. Calculated precision and accuracy data for standard OREAS-24b is presented in the Supplementary papers (Table S3) following the correction of each element. Note the excellent data quality for Sr and Rb regardless of date, poorer data quality for As regardless of date, and reduced precision for all elements on 14 May 2015 (drill-hole EC056D; most likely owing to the pXRF overheating). The following elements reported by the pXRF were discarded: Ag, Au, Bi, Hf, Sb, Sn, Mo, Th, U and W. These were rarely above LOD and were associated with large errors (e.g. Ag ±9 ppm, Sb ±20 ppm). Corrected pXRF data are presented in the Supplementary papers (Table S4).

### Magnetic susceptibility
Magnetic susceptibility measurements were taken systematically every 1 m of diamond drill-core logged on metre marks using a Fugro RT-1 Magnetic Susceptibility Meter (~2000 measurements from 10 drill-holes).

### Immobile element geochemistry
The mobility of most of the major and trace elements during hydrothermal alteration is well established in the literature (e.g. Jenner, 1996; MacLean, 1990). Only the following elements, which are demonstrably immobile during both hydrothermal alteration and amphibolite-facies metamorphism, are used here to elucidate petrogenesis: Al$_2$O$_3$, TiO$_2$, Th, Co, V, the HFSE (e.g. Nb, Y, Sc) and REE (minus...
Eu) (Jenner, 1996; MacLean, 1990; Pearce & Cann, 1973). While these elements may move on the millimetre scale during hydrothermal alteration and subsequent metamorphism (as they are transferred into new minerals), they can be considered immobile at the hand-specimen scale and particularly in sections of drill-core analysed here (~20 cm length).

The immobile element geochemistry of samples analysed from the King deposit is illustrated in Figures 10 and 11. All samples of garnet-amphibolite from the footwall of the deposit (and thin amphibolite units from the hanging-wall) are of calc-alkaline basaltic affinity according to both the Zr/TiO₂ vs Nb/Y classification diagram of Pearce (1996; Figure 10a) and the Co vs Th diagram of Hastie, Kerr, Pearce and Mitchell (2007; Figure 10d). One exception is sample GK021, which displays more intermediate geochemical characteristics (Figure 10a). This is consistent with its position near the overlying mixed footwall sequence (Figure 6c) that is dominated by more siliceous rocks. Footwall garnet-amphibolites are generally characterised by consistently high Sc (17–46 ppm) and Co (84–119 ppm) concentrations, and variable Cr (<10–150 ppm) and immobile element ratios (e.g. Zr/Y 2.2–12.8). Chondrite-normalised REE profiles show little variation between units in terms of the HREE (Dy/Yb 1.4–1.9), but there is significant LREE variation in the samples analysed (La/Yb 1.7–16.5; Figure 11d). This may be a consequence of LREE mobility in the intensely chloritised feeder zone underlying massive sulfides (e.g. Barrett & MacLean, 1994). Two samples of amphibolite analysed from the hanging-wall of the King deposit (Figure 6c) contain lower Co concentrations (Figure 10d), higher Zr/TiO₂ ratios (Figure 10a) and similar chondrite-normalised HREE profiles to those from the footwall (Figure 11d).

Rocks of intermediate composition from the mixed footwall sequence display gently dipping REE profiles (La/Yb 5.8–9.1; Figure 11e). The Zr/TiO₂ ratios, and concentrations of Th, Sc and Co, are similar to those of overlying quartz-muscovite schists at King (Figure 10b). Niobium, Y, Hf and Zr concentrations are generally higher in the intermediate volcaniclastic rocks than in the overlying felsic rocks; however, this may be a function of higher mass gain in the quartz-muscovite schists, as ratio combinations of these elements yield similar values.

Quartz–muscovite schists from the immediate footwall of the King deposit are characterised by andesitic to dacitic Zr/TiO₂ ratios (223–284; Figure 10b), and calc-alkaline Zr/Y (4.6–15.0) and La/Yb ratios (>9.0). Cr concentrations are below detection (<10 ppm), and Co concentrations are generally low (Figure 10d), both of which are consistent with a dacitic protolith. Low HFSE concentrations (<5.7 ppm Hf, 5.3–15.7 ppm Y, <0.4 ppm Ta) indicate these rocks are of FI (to FII) affinity (Figure 10e, f). Chondrite-normalised REE profiles have intermediate characteristics between felsic rocks from Nimbus and Teutonic Bore (Figure 11f).

Hanging-wall banded schists range in composition from mafic to felsic according to their Zr/TiO₂ ratios and Co concentrations (Figure 10c, d), consistent with their variations in mineralogy (quartz–biotite dominated to amphibole ± garnet) (Figure 7f). Quartz-porphyry sills, which intrude and are interpreted as coeval with the King stratigraphy (Figure 6c; labelled 1), are intermediate to dacitic in composition (Figure 10c, d), with high calc-alkaline Zr/Y (16.7–18.5) and Th/Yb ratios, and low HFSE concentrations (Figure 10e, f). Chondrite-normalised REE profiles are steep, with respect to both the LREE and HREE (Figure 11a). The younger quartz-porphyry sills (Figure 6c, labelled 2) and late basaltic dykes were not analysed.

**Mobile element geochemistry**

The mobile element geochemistry of the King deposit is illustrated in Figures 12 and 13. Regional metamorphism at King can be considered isochemical at the hand-specimen scale. Although dewatering reactions during regional metamorphism may lead to the mobility of volatile species (e.g. H₂S, F, CO₂; Corriveau & Spry, 2014; Spry, 2000), mobile element characteristics will primarily reflect hydrothermal alteration prior to metamorphism (detailed in Bonnet & Corriveau, 2007; Corriveau & Spry, 2014). Mass change values were not calculated for samples from King, as a suitable least altered precursor was not identified. Weakly altered rocks analysed from Erayinia NW (eastern Murrin Domain) have distinct immobile element characteristics and are therefore not suitable for mass change calculations at King, whereas those from King North are similarly altered to the rocks described here (Kelly, 2018).

Garnet-amphibolites from the deep footwall of the King deposit are characterised by high Fe₂O₃T (18–28 wt%), and variable Cu (75–1315 ppm) and MgO (3–13 wt%) concentrations (Figures 12 and 13). This is consistent with varying degrees of Mg-metasomatism and pyrrhotite–magnetite ± chalcopyrite ± pyrite mineralisation in the feeder zone, stratigraphically underlying massive sulfide mineralisation (Figure 6d; see Discussion). Calcium and SiO₂ concentrations are variable (39–51 wt% SiO₂, 1–18 wt% CaO) reflecting the abundance of hornblende, epidote and quartz (Figure 12). Sodium and K concentrations are low (<0.8 wt% for each), consistent with a mafic protolith. Most pathfinder element concentrations are anomalous (e.g. 2.8–15.1 ppm As, 0.3–4.2 ppm Sb) compared with unmminerallised mafic rocks from the Yilgarn Craton (Hollis et al., 2015), except for TI, Bi and Au, which are generally low (Figure 12). Very high Mo (534 ppm) was noted in sample GK004 and is being targeted for Re–Os geochronology. On a box plot of Large, Gemmell and Paulick (2001a) samples plot in both the ‘least altered mafic’ field and between the ankerite/dolomite and chloride/pyrite mineral nodes reflecting variable enrichments in Ca, Fe and Mg (Figure 12).

Intermediate banded schists from the mixed footwall sequence show increased SiO₂ (58–76 wt%) concentrations
when compared with the stratigraphically underlying footwall garnet-amphibolites and have highly variable K2O (0.3–1.4 wt%) and Na2O (0.7–2.7 wt%) concentrations. This is consistent with the intense silicification in the mixed footwall sequence (Figure 6d), together with a more evolved precursor composition (reflected by lower TiO2 concentrations; Figure 13, EC056D), and varying albitic alteration. Significantly lower Fe2O3T (2.2–7.3 wt%) and Cu (3–58 ppm) reflect the decreased abundance of chlorite, sulfide and magnetite present in the drill-core (e.g. EC116D; Figure 13). Lower Ag, As, Bi, Hg, Sb and Alteration Index (AI) values in the intermediate rocks correlate with a decreased abundance of Zn (Figures 12 and 13). All samples analysed plot with the ‘least altered andesite’ field of the box plot (Figure 12). Zones of anomalously high Ni and Cr (pXRF data) in the mixed footwall sequence correspond to tectonic schists.

Quartz–muscovite schists in the immediate footwall to massive sulfides at King are characterised by the highest SiO2 (72.5–93.4 wt%) values measured, and variable Fe2O3T (0.5–6.7 wt%) (Figure 12). This reflects the intense silicification of host rocks and variable sulfide mineralisation (pyrite ± sphalerite). Low Na2O (typically ~0.3 wt%), MgO (0.2–1.0 wt%) and CaO, correspond to lesser chloritic and albitic alteration, and Na-depletion through the sericitisation of feldspar (subsequently recrystallised to coarse muscovite during prograde metamorphism). Element concentrations may have also been increased through large mass gains of SiO2. Sample GK044 (Figure 6c) shows significantly higher concentrations of Na2O, CaO (4.3 wt%), MgO (2.5 wt%) and lower SiO2 (59.8 wt%). This sample is a coherent, weakly altered dacite surrounded by sheared and intensely silica–sercite altered dacite. It most likely represents a coherent lava flow or a high-level intrusion that is interbedded with volcaniclastic rocks of similar composition. Hydrothermal fluids would have been preferentially focused through the latter. Only sample GK044 plots within the ‘least altered dacite’ field of the Box Plot with other samples trending towards the chlorite/pyrite and sericite mineral nodes (Figure 12). Pathfinder elements vary in abundance in the quartz–muscovite schists but are commonly high (to 72 ppm Cd, 465 ppm Pb, 35 ppm Sb, >25 ppm Hg) compared with all other lithologies except massive sulfides (Figures 12 and 13). Downhole concentrations of Ni and MnO correlate well with increased amounts of Fe and base metals (Zn + Pb) in the core (EC031D; Figure 13). Arsenic concentrations increase systematically towards massive sulfides in the top ~10 m of quartz–muscovite schist in hole EC031D, with corresponding increases in Ag, Au, Sb, Tl and positive Eu anomalies (Eu/Eu*; Figure 13).

Three samples of massive sulfide were analysed from the King deposit (holes EC116D and EC113D). These rocks are characterised by high Fe2O3T (24–27 wt%) and variable Zn (0.4–15.9 wt%), reflecting the abundance of pyrrhotite, pyrite and sphalerite (Figures 12 and 13). Pathfinder concentrations of the following elements are anomalous to moderately high: Ag (28–50 ppm), As (40 to >250 ppm), Bi (2–52 ppm), Cd (95–452 ppm), Hg (>23 ppm), In (3–20 ppm), Te (4–10 ppm), Sb (6 to >250 ppm), and Se (5–25 ppm). Lead, Cu and Au concentrations are low (0.46–0.93 wt% Pb, <125 ppm Cu, <0.1 g/t Au) compared with other VHMS deposits in the Eastern Goldfields (Hollis et al., 2015). All samples display prominent positive Eu anomalies (Figure 11c). Although Sn data are considered unreliable here owing to poor accuracy and precision, massive sulfides have concentrations (27–112 ppm) well in excess of all other rocks analysed from the King deposit (typically ~2 ppm).

Hanging-wall strata (both banded schists and coherent amphibolites) are characterised by low SiO2 (<57.2 wt%). Concentrations of K2O (0.7–1.7 wt%), Na2O (0.03–2.74 wt%), MgO (1.5–7.8 wt%) and CaO (0.8–7.9 wt%) are variable (Figure 12). Iron concentrations are high (11–24 wt% Fe2O3T) reflecting the presence of abundant disseminated magnetite (with corresponding high magnetic susceptibility) and stringer pyrite (Figure 13). Thallium and Sb concentrations are moderately high and similar to the quartz–muscovite schists adjacent to massive sulfides. All samples analysed plot near the ankerite/dolomite mineral node of the Box Plot owing to a very high Carbonate–Chlorite–Pyrite Index (CCPI), but moderate AI (~50%; Figure 12). High CCPI is predominantly due to the abundance of Fe, with local carbonate alteration (Figure 9p–r). Pathfinder concentrations are typically low, except for sample GK027 (with abundant stringer pyrite), which contains high As (167 ppm) and Se (7.6 ppm). This sample displays the most prominent positive Eu anomaly from those analysed in the hanging-wall of the King deposit (Figure 11b).

**Discussion**

The nature of the host rocks, grade and tonnage of the deposit, styles of mineralisation, the observed mineralogy of the host sequence and its geochemical characteristics are all consistent with the King Zn deposit representing a metamorphosed and overturned VHMS system. We discuss each in turn and then discuss potential halos that may be used to find VHMS deposits in amphibolite facies greenstone belts of the Yilgarn Craton.

**Volcanic environment**

Although the host stratigraphy of the King deposit has been metamorphosed to amphibolite facies and is strongly deformed (e.g. Figure 7e, f), its geological features are consistent with an evolving volcanic sequence deposited in a deep-marine, rifted-arc or more likely cratonic- rift setting. Immobile element geochemistry highlights an evolution of the footwall sequence from calc-alkaline basaltic magmatism with high Co and Ti concentrations, to andesitic and...
dacitic rocks (Figures 10 and 13) capped by massive sul-
fides. The return of thin mafic lithologies in the hanging-
wall of similar composition to the footwall (Figures 10 and
11) is consistent with a shift in the geodynamic environ-
ment, possibly related to further extension (Piercey, 2011).
This cyclicity has been noted from many VHMS camps
worldwide, with mineralisation occurring towards the end
of a mafic to felsic eruptive cycle (Galley et al., 2007). It is
difficult to determine if the volcanic sequence is dominated
by flow or volcaniclastic units. However, recrystallised
quartz clasts in the some of the mixed footwall sequence,
along with the broad and diffuse alteration halo associated
with VHMS mineralisation at King, favour the latter inter-
pretation (after Gibson & Galley, 2007).

The presence of sulfide-bearing graphitic schists at sever-
ral stratigraphic horizons, including the ore horizon
(drill-hole EC116D), are indicative of a deep-marine euxinic
environment, below storm wave base, for the entire stratig-
raphy. This setting would have provided a favourable
chemical environment for the preservation of massive sul-
fides if formed on the paleo-seafloor. By contrast, if min-
eralisation formed through subseafloor replacive processes,
finely-grained sediments might have acted to seal the hyd-
othermal system (Franklin, Gibson, Galley, & Jonasson, 2005).
Owing to the extensive recrystallisation of primary textures,
it is unclear whether the King deposit formed on the sea-
floor, or through replacive processes. The thin, sheet-like
morphology of massive sulfide mineralisation might sug-
gest that mineralisation preferentially replaced a thin strati-
graphic horizon, possibly of fine-grained graphitic
sediments near the top of the quartz–muscovite schists (as
appears to be the case in EC116D; Figure 9i). The presence
of minor sulfide mineralisation (Figure 8g) and the enrich-
ment of pathfinder elements (e.g. Ti, Sb) in the immediate
hanging-wall (Figure 12) could be consistent with either a
replacive model, or seafloor exhalation if hydrothermal
activity continued after the deposition of hanging-wall
strata. Further evidence for a replacive model is the pre-
sence of milled rock fragments within massive sulfides
(Figure 8e, i). If massive sulfide mineralisation formed
predominantly through replacive processes, these clasts might
represent remnants of the unreplaced host stratigraphy
that were subsequently deformed during regional metamorphism.

The tectonic setting of the King stratigraphy is consid-
ered here with regard to the wider ‘arc vs plume’ debate
for the origin of the Eastern Goldfields (Barnes & Van
Kranendonk, 2014; Barnes, Van Kranendonk, & Sonntag,
2012; Czarnota et al., 2010; Hollis et al., 2015, 2017a). The
arc scenario, used to interpret the geochemistry of rock
types present in the Eastern Goldfields Terrane (EGS), does
not explain evidence for a common history between the
Youanmi Terrane and EGS, which includes: (1) contempor-
aneous magmatism across the EGS and Youanmi Terrane
from at least ca 2.82 Ga (Barnes et al., 2012; Ivanic,
Wingate, Kirkland, Van Kranendonk, & Wyche, 2010); (2)
simultaneous inferred ‘subduction-related’ magmatism
across the whole of the craton, which is inconsistent with
the geometry of modern arc systems (Van Kranendonk, IVanic, Wingate, Kirkland, & Wyche, 2013); and (3) strati-
ographic similarities between the Kalgoorlie and Yamarna
terranes, and Youanmi and Burtville terranes (Pawley et al.,
2012). Furthermore, recent work has also demonstrated
that mafic to felsic rocks of the EGS are geochemically con-
sistent with the fractionation of plume-related tholeiitic
basalts, coupled with their contamination by contemporan-
eous partial melts of pre-existing continental crust (Barnes
& Van Kranendonk, 2014; Barnes et al., 2012; Hayman et al.,
2015b). An arc is therefore not required.

Whole-rock geochemical data from King are shown on
the Th/Yb vs Nb/Yb plot of Pearce (2008) in Figure 10g.
The geochemical trend away from the mantle array to
higher Th/Yb ratios favours the fractionation and crustal
contamination of plume-derived basaltic magmas, rather
than subduction-related magmatism (which would parallel
the mantle array; see Bédard, Harris, & Thurston, 2013).
This trend is also present in samples analysed from Erayinia
NW (~4 km NW of King in the Murrin Domain; Hollis,
unpublished data) and at King North (Kelly, 2018).
Magmatic activity inferred to be plume-related precedes all
episodes of VHMS mineralisation in the Youanmi Terrane
(at ca 2.9 Ga, 2815 Ma, 2750 Ma and 2720 Ma; see Hollis
et al., 2015). This plume-related activity is reflected by the
repeated occurrence of komatiitic or high-Mg basaltic mag-
matism in the Youanmi Terrane, followed by the eruption
and emplacement of major extrusive/intrusive mafic suites,
terminated by felsic volcanism (Ivanic et al., 2010; van
Kranendonk et al., 2013) that hosts VHMS deposits
(reviewed in Hollis et al., 2015, 2017b). Although the age of
the King deposit is not clear, the presence of BIF and ultra-
mafic rocks in the local area, and talc schists in the King
stratigraphy, suggest it is of similar age to the Nimbus and
Anaconda deposits of the EGS (ca 2705 Ma; Hollis et al.,
2015, 2017b).

Deposit type, style, grade and tonnage
There are over 800 significant (>0.2 Mt) VHMS deposits
worldwide, mostly of small tonnage (Galley et al., 2007;
Piercey, Peter, & Herrington, 2015). Metal ratios reflect the
tectonic setting at the time of mineralisation, as metals are
derived through the leaching of underlying strata with
magmatic inputs in arc/backarc environments (Franklin
et al., 2005; Galley et al., 2007; Piercey, 2011). Deposits may
be classified as Cyprus-, Besshi-, Noranda-, Kuroko- and
Bathurst-types, corresponding to the nature of their
host rock sequences and dominant metals (i.e. mafic
Cu–Zn, mafic-siliciclastic Cu–[Co–Zn–Ni], bimodal-mafic
Cu–Zn–Pb–[Ag–Au], bimodal-felsic Zn–Pb–Cu–[Au–Ag] and
felsic-siliciclastic Zn–Pb–Cu–[Au–Ag] groups, respectively;
Franklin et al., 2005; Piercey, 2011). A sixth VHMS type (i.e.
Eskay Creek-type), rich in precious metals, reflects hybrid
deposits with both VHMS and shallow-water epithermal characteristics (Piercey, 2011).

Equivalents to most of these VHMS types are present in the Yilgarn Craton. The Teutonic Bore, Jaguar and Bentley deposits of the Kambalda Terrane (Figure 1) occur in mafic-dominated volcanic sequences, with felsic volcanic complexes and deep-marine argillaceous sedimentary rocks near the ore horizon (Belford et al., 2015; Hallberg & Thompson, 1985). Although these deposits are relatively small (1.6–3.05 Mt), Zn grades are high (9.8–11.3 wt%) and significant amounts of Cu are present (2–3.5 wt%) with minor Pb (~0.6 wt%). The Teutonic Bore deposits therefore closely resemble bimodal-mafic or Noranda-type deposits worldwide (median 3.0 Mt at 5.2 wt% Zn, 1.7 wt% Cu, 0.9 wt% Pb; Piercey et al., 2015). Bimodal-felsic or Kuroko-type deposits are typically characterised by significantly higher Pb (~1.9 wt%) and lower Cu (~1.4 wt%) concentrations (Piercey et al., 2015; Yeats et al., 2017), but are more common in Paleozoic volcanic sequences than the Archean (Huston, Pehrsson, Eglington, & Zaw, 2010). Examples of felsic-siliciclastic and hybrid-epithermal deposits in the Yilgarn Craton include the Hollandaire (Hayman et al., 2015a) and Nimbus deposits (Hollis et al., 2017a).

The current King deposit resource (2.15 Mt at 3.47 wt% Zn), while significantly smaller than VHMS deposits in the Golden Grove camp of the Youanmi Terrane (e.g. Scuddles 10.5 Mt; Figure 1), is of comparable size to most other resources in the Yilgarn Craton (e.g. Teutonic Bore 1.68 Mt, Just Desserts 1.07 Mt, Hollandaire 2.8 Mt; Austin 1.48 Mt, Manindi 1.35 Mt; see Hollis et al., 2015). The largest deposits in the Yilgarn generally comprise multiple stacked lenses of massive sulfides (e.g. Gossan Hill: Sharpe & Gemmell, 2001; Nimbus: Hollis et al., 2017a). The King deposit is classified as a metamorphosed bimodal-mafic or Noranda-type VHMS deposit, owing to the abundance of mafic to felsic volcanic rocks, low volume of siliciclastic rocks, low Pb concentrations in massive sulfides (0.47–0.93 wt%) and presence of significant chalcopyrite in the feeder zone.

Within VHMS deposits worldwide, a common metal zonation is widely observed. In bimodal-mafic deposits, feeder systems are typically dominated by Cu and Fe sulfides, primarily chalcopyrite, pyrite and/or pyrrhotite (Galley et al., 2007). Overlying lenses of massive sulfides become increasingly pyrite–sphalerite ± galena-rich and pyrrhotite–chalcopyrite poor towards the paleo-seafloor (Galley et al., 2007). Gold and Ag may be associated with Cu-rich, Zn-rich mineralisation or both (Gibson & Galley, 2007), as appears to be the case at King (Figure 13). Despite the extensive recrystallisation of sulfide assemblages at King, the zonation from a pyrite–sphalerite-rich lens of massive sulfide, stratigraphically underlain by a chloritic stockwork with abundant chalcopyrite, pyrrhotite and magnetite (Figure 6c), is consistent with Noranda-type deposits if the local stratigraphy has been overturned. No resource is available for Cu and Au, owing to the limited assaying for Au in massive sulfides, and both metals in the chloritic feeder zone. Samples analysed in this study reached 0.2 g/t Au in the footwall rocks and 0.1 g/t Au in the massive sulfides (Supplementary papers, Table S1). Historic intercepts include 5 m at 0.6 g/t Au (drill-hole EC046D) and 5.9 m at 0.3 g/t Au (EC031D). Copper concentrations reached 0.13 wt% in lithogeochemistry samples (in the garnet-amphibolite), with corrected pXRF spot analyses reaching a maximum of 0.7 wt%.

### A metamorphosed hydrothermal system

Primary alteration minerals surrounding VHMS deposits include chlorite, sericite, carbonate, quartz and pyrite, with talc, epidote, albite and kaolinite (or in places other clay minerals) commonly present (Barrett, MacLean, & Arebäck, 2005; Galley et al., 2007; Yeats et al., 2017). In upper greenschist- to amphibolite-facies metamorphic terranes, distinctive coarse-grained mineral suites commonly define VHMS alteration zones (Dusel-Bacon, 2012; Galley et al., 2007). These minerals can include, but are not limited to: chloritoid, garnet, staurolite, kyanite, andalusite, phlogopite, and garninite (zincian spinel). The presence or absence of each of these minerals reflects not only VHMS-style hydrothermal alteration and P–T conditions during metamorphism, but also the thermal gradient during metamorphism (Dusel-Bacon, 2012). A comprehensive list of metamorphosed VHMS deposits under different conditions (e.g. greenschist, granulite, blueschist), and common minerals associated with each, was given by Corriveau and Spry (2014).

Hydrothermal alteration at King is dominated by quartz–muscovite ± chlorite ± albite ± carbonate in felsic to intermediate banded schists, and quartz–epidote ± chlorite ± magnetite in garnet-amphibolite. Cordierite and anthophyllite also occur in relatively minor amounts (<5 vol%) in felsic to intermediate footwall rocks. According to Corriveau and Spry (2014), the ‘best documented alteration types associated with metamorphosed VHMS deposits are the cordierite-anthophyllite schists, commonly the amphibolite facies analogues of chloritic alteration pipes’ (p. 181). Their distinct lithogeochemical signature (±Mg, ±Fe, –Ca, –Na, –K) results in mineral assemblages that may include cordierite, orthoamphibole/orthopyroxene, Al₂SiO₅ polymorphs, garnet or staurolite, quartz, biotite and plagioclase, depending on P–T conditions. The aluminous minerals garnet, chloritoid, staurolite and the Al₂SiO₅ polymorphs (~andalusite, kyanite, sillimanite) commonly occur close to high-T alteration pipes. This reflects the enrichment of Al by leaching of alkalis under high fluid/rock ratios (Dusel-Bacon, 2012). Metamorphosed phyllic, sericitic and argillic alteration zones (±K, ±Mg, ±Fe, –Ca, –Na) will result in the formation of diagnostic peraluminous and/or mica-rich metamorphic rocks (e.g. those unusually rich in Al₂SiO₅ polymorphs, cordierite, garnet, K-feldspars and/or micas) (Corriveau & Spry, 2014).
At King, the abundance of silica–epidote in the footwall garnet-amphibolites is consistent with typical seafloor alteration of basaltic rocks prior to metamorphism (Galley et al., 2007). Prograde metamorphism of an Al-rich assemblage of basaltic rocks is also recorded by the presence of abundant garnet, with hornblende and biotite. Garnet can locally form up to 50 vol% of the rock (Figure 7a—upper core), which has been widely retrogressed to chlorite and quartz. The Cu–Fe sulfide-bearing zone rich in chlorite and magnetite within the footwall garnet-amphibolites is consistent with a stockwork zone that generally underlies lenses of massive sulfides that have been metamorphosed (Galley et al., 2007). The LREE variation in these footwall rocks has also been observed in intensely chlorite-altered stockwork zones elsewhere (e.g. Barrett & MacLean, 1994).

In overlying intermediate and felsic rocks, the presence of significant Mg-rich cordierite and anthophyllite may also be taken as evidence for Mg-metasomatism prior to metamorphism (Barrett et al., 2005; Corriveau & Spry, 2014). Anthophyllite and cordierite are present within other metamorphosed VHMS footwall rocks of the Yilgarn Craton. Anthophyllite has been identified from the Just Desserts deposit (1.07 Mt at 1.82 wt% Cu; Hassan, 2014), and in the Quinns district associated with the Austin deposit (1.48 Mt at 1.39 wt% Zn, 1.02 wt% Cu; Duuring et al., 2016). Cordierite-rich rocks have been identified associated with VHMS mineralisation at Ravensthorpe (Witt, 1999), and Mount Gibson (Yeats & Groves, 1998).

The transition from chloritic and albitic alteration in intermediate lithologies to quartz–muscovite alteration in the overlying dacitic rocks (with lower TiO₂; Figure 13) reflects increased sericitisation (+K, −Na, −Ca, −Mg) towards mineralisation in footwall rocks prior to metamorphism. The intermediate rocks analysed here are generally only weakly altered (Figure 12; see box plot). In the footwall quartz–muscovite schists, prograde metamorphism led to the recrystallisation of an assemblage most likely dominated by quartz–sericite ± pyrite ± (chlorite). These rocks are now dominated by fine granoblastic quartz with interstitial platy muscovite. Minor epidote, garnet and hornblende became sinks for Ca, Al, Fe, Mg and Na. Subsequent retrograde metamorphism is recorded by the replacement of the coarse muscovite by sericite and Mg-chlorite, sericitisation of cordierite and breakdown of garnet to chlorite and quartz.

Most VHMS deposits worldwide metamorphosed to amphibolite facies are characterised by at least one Al-rich phase (Araujo, Fawcett, & Scott, 1995). Alteration assemblages containing Al-rich mineral phases are interpreted to represent the removal of SiO₂ and alkali elements by acidic fluids, and the residual concentration of Al₂O₃ in footwall rocks prior to metamorphism (Duuring et al., 2016; Galley et al., 2007). Staurolite porphyroblasts have been recognised surrounding the Hollandaire deposit with garnet (Hayman et al., 2015a), and at Wheatley with garnet, sillimanite and kyanite (Hassan, 2017a; Yeats, 2007) (Figure 1). Andalusite has been identified in metamorphosed sedimentary and felsic rocks from the Dalgaringa greenstone belt (Superior Zn prospect; Butt & Sergeev, 2003), in altered footwall rocks at Teutonic Bore (albeit in minor amounts; Hallberg & Thompson, 1985), at Hollandaire (with kyanite; Hayman et al., 2015a) and in the Quinns district (with kyanite; Tasman and Franklin prospects: Duuring et al., 2016; Hassan, 2017b) (Figure 1). Minor andalusite was also reported by Sharpe and Gemmell (2001) from the strata-bound chlorite–(carbonate) alteration enveloping massive magnetite and sulfide mineralisation at Gossan Hill. More globally, the Archean Geco deposit of the Superior Province, Canada, is a well-studied example of a bimodal VHMS deposit metamorphosed to upper amphibolite facies. Ore-hosting lithologies now comprise muscovite–quartz ± sillimanite schist, interpreted as a metamorphosed sericitic alteration zone (Dusel-Bacon, 2012).

Research on the Kristineberg VHMS deposit of lower amphibolite facies from the Skellefte district, Sweden, has shown that very different secondary assemblages such as andalusite–quartz–muscovite and cordierite–chlorite–talc can both be produced from the same precursor (e.g. rhyolite); and conversely the same mineral assemblages can also be produced from different precursor rocks, such as a weakly altered andesite and strongly altered rhyolite (Barrett et al., 2005). The authors proposed a series of reactions to explain the observed mineralogy at Kristineberg (namely quartz, Mg-chlorite, muscovite, cordierite, phlogopite/biotite, andalusite and pyrite). The most significant reactions here are:

1. 280 chlorite +131 quartz → 231 cordierite +180 anthophyllite + water
2. 40 chlorite +28 sericite +9 quartz → 33 cordierite +32 phlogopite +12 andalusite +16 water
3. 140 chlorite +49 sericite +51 quartz → 141 cordierite +56 phlogopite +30 anthophyllite + water

The numbers before mineral names give the Niggli cation amounts of each mineral involved in the reactions. Note that the major difference between the second and third equations is the proportion of chlorite. When this is higher (eq. 3), cordierite, phlogopite/biotite and anthophyllite may be produced without andalusite (Barrett et al., 2005). This may explain the prevalence of cordierite and anthophyllite (plus biotite) at King. Although we cannot rule out the presence of an Al₂SiO₅ phase, none were observed in thin-section or under SEM.

**Prospectivity of felsic rocks**

The immobile element geochemistry of felsic volcanic rocks has long been used to distinguish VHMS fertile from unprospective camps (Hart et al., 2004; Lesher et al., 1986; Piercey, 2011). Quartz–muscovite schists of dacitic composition from King display similar geochemical characteristics
to felsic rocks associated with VHMS deposits throughout the Yilgarn Craton (Hollis et al., 2015, 2017a), but with subtle differences. VHMS-associated felsic rocks throughout the Yilgarn are characterised by: (1) high SiO₂ in unaltered rocks; (2) tholeiitic to transitional Zr/Y and La/Yb values (i.e. FII to FIII affinity; Figure 14b); (3) flattish REE profiles (La/SmCN < 3, Dy/YbCN ~ 1); (4) high HFSE concentrations; (5) high Sc/TiO₂ and Sc/V ratios; and (6) low Th/Yb ratios (<2) (Hollis et al., 2015, 2017a). These felsic rocks are also equivalent to those that host VHMS deposits of the Pilbara Craton of Australia (Vearncombe & Kerrich, 1999) and the Abitibi greenstone belt of Canada (Barrie et al., 1993; Figure 14a). One exception is the Nimbus Ag–Zn–(Au) deposit, near Kalgoorlie, which is hosted by FI affinity calc-alkaline dacite (Figures 11f and 14b; Hollis et al., 2017b). Precious metal-rich VHMS deposits (i.e. Eskay Creek-type deposits) typically form at shallower water depths to classic Zn–Cu deposits and are commonly hosted by 'less prospective' FI- to FII affinity, calc-alkaline rocks (Mercier-Langevin, Hannington, Dubé, & Bécu, 2011; Figure 14a).

Although quartz–muscovite schists from King, display similar Zr/Y (4.6–15.0) and La/Sm ratios to felsic rocks from Teutonic Bore, HFSE concentrations are significantly lower (e.g. 68–236 ppm Zr; Figure 10e, f) and HREE profiles are slightly steeper (Figure 11f). While the HFSE depletion in the King felsic rocks may be a function of element dilution through mass gain, this would not explain higher Dy/Yb...
ratios. The FI (to FII) characteristics at King (Figure 10e, f) might suggest reduced base-metal prospectivity for the immediate area, in keeping with lower grades of Zn mineralisation and abundant occurrences of massive Fe sulfides. However, the geochemistry of felsic rocks further into the hanging-wall or footwall of the stratigraphy has not been tested. Furthermore, at King North (Figure 4), recent geochemical work on rock chips from RC drilling...
Duuring Mn and V) were noted from the Quinns VHMS region by MgO, Mo, S, Se and Te (with minor enrichments in As, Cd, VHMS proximal metal enrichments of Ag, Au, Bi, Fe, In, footwall sequence, quartz–ments show a progressive increase in abundance from the immediately underlying massive sulfides (Figure 12) and moderately high and similar to quartz–feldspar at temperatures >250°C (Sverjensky, 1984). This leads to prominent positive Eu anomalies in hydrothermally altered and mineralised volcanic rocks, as observed at King (Figure 11), Nimbus (Hollis et al., 2017a) and other VHMS deposits in the Yilgarn (Hollis et al., 2015).

Chemographic ternary diagrams are useful for portraying common alteration trends in metamorphosed terranes, as shown in Figure 15 (Bonnet & Corriveau, 2007; Corriveau & Spry, 2014). Whereas samples of footwall garnet- amphibolite from the King deposit plot towards the garnet, chloride and hornblende mineral nodes, samples of quartz–muscovite schist plot towards the cordierite node and A’ corner (i.e. Al-rich end) of the diagram (Figure 15a). The former is interpreted to reflect the intense Mg–Fe metasomatism of the feeder zone, and the latter both quartz ± sericite ± pyrite alteration and Al-enrichment through alkali leaching of felsic volcanic rocks prior to metamorphism. Weakly altered samples from the mixed footwall sequence and intrusive quartz–feldspar porphyries plot closer to the least altered volcanic field. Data from the Teutonic Bore and Wheatley deposits are also shown for comparison (Figure 15b, c). The intensity of Fe and Mg enrichment at Teutonic Bore is highlighted by the strong clustering of both mafic and felsic footwall strata between cordierite and garnet. At Wheatley, mineralised felsic gneisses plot towards the cordierite mineral nodes, whereas hanging-wall amphibolites are weakly altered.

In metamorphosed terranes, the Mn contents of ferro-magnesian minerals such as garnet, biotite, staurolite, chlorite and amphibole have been observed to increase with proximity to sulfide deposits, as well as the Zn content of staurolite and spinel (i.e. gahnite) (Corriveau & Spry, 2014). The pink colour of garnets at King suggests they are Mn-rich (i.e. spessartine). MnO concentrations in the King footwall garnet-amphibolite reach 1.3 wt% in sample GK021. Large Mn peaks were also identified in garnet EDS spectra. Spessartine garnet porphyroblasts have been observed in hanging-wall and footwall strata surrounding VHMS mineralisation in the Yilgarn Craton at both Hollandare and Wheatley (Hassan, 2017a; Hayman et al., 2015a). Elevated contents of Mn in garnet from garnetites, and Zn in spinel from aluminous gneisses were recently noted from granulite-facies rocks in the central Grenville Province, Canada, highlighting its potential for VHMS mineralisation (Hindemith, Indares, & Piercey, 2017). Corriveau and Spry (2014) have further suggested that staurolite becomes increasingly orange with Zn content. This may prove useful to identify further resources at Hollandaire and other regions where staurolite porphyroblasts surround mineralisation (Hayman et al., 2015a).

As regional metamorphism is largely an isochronal process at the core scale, combinations of indices such as Ishikawa AI, CCPI (Large et al., 2001a), the Silicification Index (100 × SiO2/SiO2+Al2O3) and the ACNK Index (Al2O3/CaO + Na2O + K2O; Grunsky, 2013) may be used to discriminate between different styles of footwall alteration and help locate mineralisation. Alteration indices and pathfinder elements are plotted against vertical distance to mineralisation at King in Figure 16. Zinc and Fe concentrations are
Figure 16. Geochemical and mineralogical vectors to mineralisation at King, plotted as distance to massive sulfide mineralisation (calculated perpendicular to ore in section 6538650 mN; Figure 6c). Normative CIPW quartz and cordierite abundances (vol%) were determined using the Norm 4 spreadsheet of Kurt Hollocher (Union College).
erratic in footwall rocks using both lithogeochemical and pXRF datasets. Vanadium concentrations are highest in the feeder zone and may be useful to identify such rocks elsewhere, particularly when combined with high Al, ACNK Index values and the abundance of normative corundum. Antimony, Tf, In and Eu/Eu\textsuperscript{a} remain low in both footwall and hanging-wall strata, only increasing significantly within short distances (tens of metres) to mineralisation. These are consequently only of use for exploration when elevated. The ACNK Index and Al are high both in the chloritic zone and directly underlying massive sulfides. The Silification Index by contrast peaks in hanging-wall strata directly overlying massive sulfides.

The abundance of calculated normative corundum was used by Grunsky (2013) for rocks from the Abitibi greenstone belt, Canada. When Al is in excess over (Ca + Na + K), the presence of normative corundum may be interpreted as extensive alkali leaching, a characteristic feature of footwall alteration associated with VHMS deposits. At King, normative corundum abundance is highest in the chloritic feeder zone, but importantly is not present (i.e. >0) in any hanging-wall strata regardless of composition. This reflects the lack of alkali leaching in the hanging-wall and may be a useful tool to identify hydrothermal upflow zones associated with VHMS deposits, and also discriminate hanging-wall from footwall sequences. Normative quartz abundance generally parallels the Silification Index trend but drops in weakly altered hanging-wall strata.

Conclusions

The King Zn deposit (2.15 Mt at 3.47 wt% Zn) occurs as a 1–7 m-thick stratiform lens dominated by Fe sulfides, in a structurally overturned volcanic-dominated sequence located ~140 km east of Kalgoorlie. The local stratigraphy is characterised by garnet-amphibolite and strongly banded intermediate to felsic schists with rare horizons of graphitic schist and tali schist. Sulfide mineralisation is dominated by stratiform pyrite–pyrrhotite–sphalerite, with pyrite–(sphalerite) and pyrrhotite–pyrite–(chalcopyrite) stringers at depth. The King deposit is classified as a metamorphosed bimodal-mafic or Noranda-style VHMS deposit.

Footwall garnet-amphibolites are of sub-alkaline basaltic affinity, with high Co and Sc concentrations, and flat chondrite-normalised HREE profiles. SiO\textsubscript{2}, CaO, Fe\textsubscript{2}O\textsubscript{3}, MgO and Cu concentrations are highly variable, reflecting quartz–epidote ± chlorite ± magnetite ± sulfide alteration. Chlorite ± magnetite alteration is most intense in the discordant Cu-bearing chloritic feeder zone. Intermediate rocks are predominantly of calc-alkaline affinity and are similar to andesites from elsewhere in the Kurnalpi Terrane (e.g. Teutonic Bore). Although footwall quartz–muscovite schists display similar Zr/Y and La/Sm ratios to felsic rocks from other Archean VHMS deposits, HFS concentrations are significantly lower, and HREE profiles are steeper. Hydrothermal alteration in felsic to intermediate rocks is characterised by a mineral assemblage of quartz–muscovite ± chlorite ± albite ± carbonate. Cordierite and anthophyllite are locally significant and indicative of zones of Mg-metasomatism prior to metamorphism. Increases in SiO\textsubscript{2}, Fe\textsubscript{2}O\textsubscript{3}, and depletions of Na\textsubscript{2}O, CaO and MgO occur in footwall quartz–muscovite schists approaching massive sulfide mineralisation.

Within all strata (including the immediate hanging-wall), the following pathfinder elements are strongly correlated with Zn: Ag, As, Au, Bi, Cd, Eu/Eu\textsuperscript{a}, Hg, In, Ni, Pb, Sb, Se and Ta. These geochemical halos resemble less metamorphosed VHMS deposits across the Yilgarn Craton and suggest that although metamorphism leads to element mobility and mineral segregation at the thin-section scale, assay samples of ~20 cm length are sufficient to vector to mineralisation in amphibolite facies greenstone belts of the EGS. Recognition of minerals such as Mg-chlorite, muscovite, cordierite, anthophyllite, biotite/phlogopite and abundant garnet are significant, in addition to Al-rich phases (kyanite, sillimanite, andalusite and/or staurolite) not present at King. Chemographic diagrams (e.g. A’KF and AFM) may be used to identify and distinguish different alteration trends, along with the following alteration indices: Ishikawa Al, Sericite Index, Silification Index, ACNK Alteration Index

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