Targeting VHMS mineralization at Erayinia in the Eastern Goldfields Superterrane using lithogeochemistry, soil chemistry and HyLogger data

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ABSTRACT

Exploration for volcanic-hosted massive sulfide (VHMS) deposits in the Archaean Yilgarn Craton of Western Australia is hampered by a combination of a paucity of outcrop, deep weathering, and saline groundwaters in geologically complex greenstone belts. We present a detailed account of the geology at Erayinia NW (Murrin Domain) in the southern part of the Kurnalpi Terrane, ~150 km SE of Kalgoorlie and 4 km NW of the King VHMS deposit (Edjudina Domain). We have used a combination of logging, petrography, lithogeochemical, pXRF, hyperspectral and soil datasets to help identify VHMS proximal signatures for future drill testing.

Diamond drilling at Erayinia NW has identified widespread hydrothermal alteration and minor base metal mineralization across a strike length of at least 3 km. A lower package of calc-alkaline metabasalt, is overlain by intermediate volcanic and associated volcaniclastic rocks, a mixed sequence of argillaceous sedimentary rocks interbedded with FI to FII affinity dacitic rocks, and calc-alkaline metabasalt. SHRIMP U-Pb zircon geochronology has constrained the age of the host stratigraphy to 2685 ± 5 Ma. Hydrothermal alteration (quartz-sericite-pyrite) is most prevalent in the 50-75 m thick felsic dominated sequence interbedded with black shales, with local zones of chloritization associated with minor Zn-Pb mineralization. Massive pyrite was intercepted in the two southernmost holes located approximately 300 m apart.

Black shales and hydrothermally altered felsic rocks contain elevated Ag, As, Bi, Cd, Cu, Hg, In, Mo, Pb, Sb, Te, Ti associated with increasing Zn concentrations. Broad halos of Sb, Tl, Eu/Eu* and normative corundum define the stratigraphy of interest. Hydrothermally altered felsic rocks are characterized by higher abundances of white mica and lesser chlorite than surrounding strata. Increased quantities of Mg-rich chlorite, muscovitic (Al-rich) white mica, and Fe-carbonate (siderite) occur proximal to Fe-Zn mineralization. Significant enrichments in trace elements (Ag, As, Bi, Cd, In, Mo, Ni, Sb, Sn, Te, Ti) associated with Alteration Index and K2O; and lower Al, Ba, Sr) in black shales towards drillholes EC154D and EC157D suggest this area is most proximal to VHMS mineralization. Soil metal concentrations vary significantly according to underlying regolith type (e.g. colluvium, alluvium, playa lake). Geochemical data levelled by regolith type reveal several bulls-eye multi-element geochemical anomalies (e.g. Zn, Pb, Cu, As, Bi, Cd, Mo, Sn, Tl, W) over the King deposit (2.15 Mt. at 3.47 wt% Zn), King North occurrence (e.g. 1 m at 6.7 wt% Zn + Pb), with new targets identified at Erayinia NW and elsewhere for future drill testing.

1. Introduction

Volcanic-hosted massive sulfide ( VHMS) deposits represent significant resources for both base and precious metals in the Earth's crust. Despite the similar age and geology of the Archaean Yilgarn Craton, Australia, and the Abitibi-Wawa subprovinces of the Superior
Province, Canada, the disparity between the numbers of discovered deposits is striking (Huston et al., 2014; Hollis et al., 2015a). The Abitibi-Wawa subprovince is host to over 83 VHMS deposits with an aggregate geological tonnage of ~730 Mt. and an in-ground metal content of 26.4 Mt. Zn, 11.3 Mt. Cu, and 0.7 Mt. Pb (Franklin et al., 2005, Huston et al., 2014). In the Yilgarn Craton (Fig. 1), less than two dozen resources have been defined for a total in-ground metal content of 3.4 Mt. Zn, 0.9 Mt. Cu and 0.3 Mt. Pb (resources of Hollis et al., 2015a, 2017a). Furthermore, production to date has been almost entirely from two camps – Golden Grove (Gellie et al., 2017) and Teutonic Bore (Parker et al., 2017).

In the c. 2.95 Ga Golden Grove camp (Youanmi Terrane, Fig. 1) numerous orebodies have been mined between Gossan Hill and Scud-dles (McConachy et al., 2004; Gellie et al., 2017). Significant resources are predominantly restricted to the uppermost members of the Golden Grove Formation, itself part of the ~3 km thick Gossan Hill Group (Sharpe and Gemmell 2002; Gellie et al., 2017). This highlights the strong stratigraphic control on mineralization that must be targeted once a favourable volcanic sequence has been identified. In the c. 2690 Ma Teutonic Bore Volcanic Complex (Kurnalpi Terrane, Fig. 1), three deposits have been mined with an aggregate production of 5.4 Mt. at 9.6 wt% Zn, 2.6 wt% Cu and 126 g/t Ag, and resources of 3.7 Mt. at 7.0 wt% Zn, 1.4 wt% Cu and 111 g/t Ag (Parker et al., 2017). The Noranda district, of comparable size to the Teutonic Bore region, contains over 20 economic deposits (Gibson et al. 2005). While some of this discrepancy has been explained through the reduced prospectivity of the Yilgarn Craton (Huston et al., 2014), it is unlikely that there are no more significant discoveries to be made (discussed in Hollis et al., 2017b). Recent successes in the Yilgarn Craton include new resources at Hollandaire and Austin in the Cue Zone of the Youanmi Terrane (Hayman et al., 2015a; Duuring et al., 2016; Fig. 1), and the recognition of significant Zn-Ag-(Au) sulfide mineralization at Nimbus near Kalgoorlie (Hollis et al., 2017a; Caruso et al., 2018).

At Erayinia in the southern Kurnalpi Terrane (Fig. 1), geophysical methods have had limited success in identifying and locating mineral deposits. Geophysical responses from conventional airborne VTEM
surveys in the region are strongly affected by conductive sediments, hypersaline groundwater, and units of black shale within the host stratigraphy. Furthermore, relics of an Eocene marine transgression are scattered throughout the region, and several large salt/playa lakes drain the local area. Consequently, the current landscape is characterized by limited outcrop, and bedrock obscured by deep and variable cover. Here we have used a combination of logging, petrography, lithochemical, pXRF, hyperspectral and soil datasets to identify VHMS proximal signatures for future drill testing ~4 km northwest of the King deposit (2.15 Mt. at 3.47 wt% Zn; Hollis et al., 2019).

2. Geology

2.1. Regional geology

The regional geology of the Erayinia area (Fig. 2) in the southern Kurnalpi Terrane is detailed in the 1:100,000 Geological Survey of Western Australia (GSWA) explanatory notes (Jones, 2007). The Claypan and Roe Hills faults divide the area into the Edjudina, Murrin and Menagina domains (Fig. 2) - of which, only the first two are of interest here.

The Edjudina Domain along its ~300 km length (Fig. 1) is dominated by several, variably metamorphosed basaltic to rhyolitic volcanic complexes, and laterally extensive belts of intermediate schist (Swager, 1995, 1997). Prominent, though volumetrically minor, marker beds of banded iron formations (BIF), chert and mudstone, chert, siltstone, sandstone and conglomerate (Jones, 2007). Several anticlines and synclines are present throughout the region, which trend northwest-southeast (Fig. 2). A metasiltstone unit in the Karonie mine has previously yielded a SHRIMP U–Pb zircon age of 2703 ± 5 Ma (Wingate and Bodorkos, 2007a), whereas a rhyolitic volcaniclastic rock from the Erayinia NW area (~4 km northwest of King) has yielded an igneous crystallization age of 2680 ± 5 Ma (Wingate and Bodorkos, 2007b) (Fig. 2). The stratigraphy of five holes (1518 m total length) drilled by Black Raven Mining from Erayinia NW are described in Section 2.2, with a new SHRIMP U–Pb zircon age presented here. Our new U–Pb zircon age is consistent with previous geochronology (Wingate and Bodorkos, 2007b), indicating a Gondwana age of ~1.8 Ga (2680–2680 Ma; Fig. 3) for the stratigraphy immediately west of...
the Claypan Fault.

Metamorphism in the Erayinia region is most intense (upper amphibolite facies) surrounding large granitic bodies (Witt, 1991; Nelson, 1997; Swager et al., 1997). Lower grade zones of greenschist facies metamorphism occur in the central parts of greenstone belts (Jones, 2007). It is important to note that metamorphic grade increases suddenly across the Claypan Fault from predominantly greenschist facies at Erayinia NW to lower amphibolite facies at King (Fig. 2).

2.2. Geology of the Erayinia NW area

During 2014 and 2015 five holes were drilled ~4 km NW of the King deposit and west of the Claypan Fault (Fig. 2) to characterize the local stratigraphy of the Murrin Domain and target VTEM (Versatile Time Domain Electromagnetic system) anomalies for potential VHMS mineralization. Holes EC154D to EC156D were drilled first. Following the recognition of favourable hydrothermal alteration assemblages and minor base-metal mineralization in the southernmost two holes (e.g. 19 m at 0.4% Zn EC155D), it was decided to explore further south where a gossan was identified in outcrop. This was subsequently drilled (holes EC157D and EC158D ~300 m apart) with intercepts of massive pyrite (1.4–1.7 m thick) and minor base-metals (4 m at 0.2% Zn, 15 m at 0.1% Cu in EC157D). The interpreted stratigraphy across the drilled area is presented in Fig. 4, with the principal lithologies described below and shown in Fig. 5. All holes were drilled at an inclination of 60° and azimuth of 270°. Rare horizons of graded bedding (mm to cm-scale) within felsic volcaniclastic lithologies are consistent with an upwards-bioturbated nature of orientations in drillcore. Pale grey, banded shale units in drillhole EC156D is quartz-feldspar phyric and quartz-sericite altered (Fig. 5j). The felsic rocks are also often interbedded with black shales (Fig. 4), and can contain angular fragments of shale as rip-up clasts (Fig. 5d). A coherent felsic unit hole in drillhole EC156D is quartz-feldspar phric and quartz-sericite altered (Fig. 5k), though its contacts with adjacent units are unclear due to the broken nature of the core.

Black shale horizons are variably graphitic, with abundant pyrite - either present as disseminated coarse euhedral crystals, veinlets, or as large diagenetic nodules (Fig. 5i). The latter are associated with the more graphitic units, and were observed at a similar stratigraphic level (except in drillhole EC158D which are largely faulted out; Fig. 4). The felsic rocks are strongly sheared, mineralized (pyrite with lesser sphalerite), and variably quartz-sericite altered (Fig. 5j). The felsic rocks are also often interbedded with black shales (Fig. 4), and can contain angular fragments of shale as rip-up clasts (Fig. 5d). A coherent felsic unit hole in drillhole EC156D is quartz-feldspar phric and quartz-sericite altered (Fig. 5k), though its contacts with adjacent units are unclear due to the broken nature of the core.

Black shale horizons are variably graphitic, with abundant pyrite - either present as disseminated coarse euhedral crystals, veinlets, or as large diagenetic nodules (Fig. 5i). The latter are associated with the more graphitic units, and were observed at a similar stratigraphic level in all holes (Fig. 4). Pressure shadows around pyrite nodules may contain chalcocylite or secondary malachite. Shale horizons are often intensely brecciated and tightly folded, with bedding showing a range of orientations in drillcore. Pale grey, banded shale units in drillhole EC155D are associated with significant sphalerite (e.g. 7 wt% Zn in geochemistry sample ER-13).

Intermediate volcaniclastic rocks and metasediments. Below the shale horizons and felsic metasediments in holes EC154D, EC155D and EC156D is a ~100 m thick package of relatively homogenous intermediate volcaniclastic rocks (Fig. 4). These rocks are less mineralized, more banded in appearance, strongly foliated and contain small (< 1 cm) angular black shale fragments and occasional large pebbles and cobbles of quartz-rich material (Fig. 5e). Evidence for hydrothermal alteration is weak except for zones of silicification.

Intrusive rocks: The volcanic-dominated stratigraphy of the Erayinia
Fig. 4. Geological logs for the five diamond drillholes from Erayinia NW. Lithogeochemistry and U-Pb geochronology samples are indicated by coloured circles and white stars respectively. A to O correspond to photographs from Fig. 5.
NW area has been intruded by myriad thin quartz-feldspar porphyritic sills, and a series of large granodiorite and quartz monzonite plutons (Fig. 4). The coarse-grained granitic rocks are best exposed in holes ED154D and EC158D where intrusive relationships are well preserved (Fig. 5a). The quartz monzonite unit at the top of EC154D (Fig. 4) contains xenoliths (1-3 cm) of foliated amphibolite and is present as xenoliths in the upper quartz-feldspar porphyry units (Fig. 5b). Contacts with amphibolite are often associated with intense silicification, quartz-brecciation and bleaching of the amphibolite. The EC145D quartz monzonite intrusion (or a similar intrusion) is also present in the uppermost weathered section of drillhole EC155D - as both coarse-grained granitic rocks and quartz-feldspar porphyritic units were observed as saprock. Thinner units of quartz monzonite and granodiorite occur at depth in drillhole EC154D (Fig. 4) with intrusive upper and lower contacts.

Thin sills (0.5-3 m) of quartz-feldspar porphyry are abundant in all Erayinia NW drillholes. At least two generations have been identified based on field relationships - though they are difficult to discern in drillcore. An early set appears to be broadly coeval with the volcanic stratigraphy as some quartz-feldspar porphyry units display peperitic contacts with black shale (Fig. 5c). These rocks are also bleached and quartz-sericite altered in drillhole EC157D, with evidence for hydraulic fracturing (Fig. 5n). A second set of quartz-feldspar porphyry sills are intimately associated with, but younger than, the larger granitoid intrusions described above. These intrusions chill against (Fig. 5a), and contain xenoliths of, the granitic rocks (Fig. 5b). All porphyry sills are weakly foliated with disseminated pyrite.

2.3. Regolith-landform setting

Due to a shift from wet, humid conditions in the Paleogene, to the prevalence of semi-arid conditions since the Neogene, the Yilgarn Craton is marked by deep weathering and complex regolith profiles (Anand and Paine, 2002). A detailed account of the climate, physiography, and regolith of the Erayinia region was presented by Jones (Anand and Paine, 2002). A detailed account of the climate, physiography, and regolith of the Erayinia region was presented by Jones (2007), which is briefly summarised here (Fig. 6). Further classification of the regolith through satellite imagery is hampered by a lack of significant relief and dense vegetation.

Overall, the terrain at Erayinia is irregular with isolated low ridges, broad sheetwash plains, and ephemeral streams. Creeks form large drainage patterns, and a series of playa lakes occur in the King and Erayinia NW drilling areas (Fig. 6). Together, these surficial deposits, a deep weathering profile, and thick colluvium, obscure much of the local geology (Fig. 6). Residual lateritic profiles are typically characterized by ferruginous duricrust over Archaean metasedimentary rocks, granite (to a lesser extent), and Cenozoic basalt. Residual material over granite is predominantly a clay and quartz-sand rich soil. Soils are highly calcareous to the south, becoming less calcareous both to the north and west.

Colluvium and sheetwash deposits were defined by Jones (2007) based on the slope of which they lie. Colluvium varies from quartzofeldspathic in composition adjacent to granitic rocks, to calcare- or lithic-rich varieties elsewhere. Sheetwash deposits are typically composed of clay, sand, silt, calcite and silcrete fragments, lithic clasts, and minor amounts of ferruginous material. Sandplain deposits are dominated by orange quartz sand. Alluvium is composed of clay, silt, sand and gravel, with significant amounts of calcrite in northern Erayinia.

Relics of an Eocene marine transgression (the Eundynie Group) are also scattered around the areas of historic and recent drilling (Fig. 6). These deposits are typified by deltaic to marine sedimentary rocks in paleodrainage channels, deep weathering profiles, and lateritization (see Jones, 2007). Eocene paleodrainage patterns were similar to the present-day systems.

3. Methods

3.1. Whole rock geochemistry

A total of forty-eight half-core samples from the Erayinia NW area (Fig. 4) were analysed for whole rock geochemistry at ALS Laboratories (Perth, Western Australia) to characterize the local stratigraphy and determine the intensity and extent of hydrothermal alteration. Major element concentrations were determined by four acid digestion and ICP-OES finish on fused glass beads. Trace, 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/metalloids (e.g. As, Sb, Ti, Bi) were determined by multi-acid digest, 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 198 half-core assay samples from the same five drillholes, along with 876 portable X-ray Fluorescence (pXRF) spot measurements. Samples of half-core were analysed at ALS Laboratories (Perth) using four acid digest (perchloric, nitric, hydrochloric) and analysis of 48 elements by ICP-MS/AES. As the four-acid method does not provide reliable data for HFSE and REE concentrations, only select major and trace element data was used for lithogeochemistry.

pXRF spot measurements were taken down hole at 1-2 m intervals using an Olympus InnoveX Systems Delta 2012 series (total counting time 60 s per analysis, 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 and Devine, 2014). Although the accuracy of pXRF data ranges widely from excellent (< 7% Relative Difference, RD) to poor (± 20% RD; see Piercey and Devine, 2014), and often needs correcting (e.g. Fisher et al., 2014; Le Valliant et al., 2014), downhole profiles replicate the geometry of those obtained from conventional analyses (Piercey and Devine, 2014; Hollis et al., 2019). Data were corrected using eleven standards from OREAS (OREAS-22d, 24b, 24c, 36, 38, 70b, 76b, 291, 931, 935, 991) for the following elements, after the method reported by Hollis et al. (2019): Cu, Fe, Ni, Pb, Rb, Sr, Ti, Y, Zn, Zr. These standards cover a wide range of concentrations for each element (e.g. 38 ppm to 12.4% Cu, 4.45-23.6 wt% Fe). Calibration equations were obtained by plotting certified concentrations against obtained pXRF values for each element. Further detail on pXRF calibration is provided in Hollis et al. (2019).
Fig. 6. Regional regolith map (after Jones, 2007) with the position of soil samples and drillholes indicated.
3.2. Spectral reflectance

Several studies in recent years have demonstrated the effectiveness of hyperspectral techniques to aid VHMS exploration (e.g. Herrmann et al., 2001; Van Ruitenbeek et al., 2012; Hassan, 2014, 2017; Guilliamse, 2014; Duurring et al., 2016). Systematic shifts in chlorite (Fe/Mg ratio), white mica (Al content), and/or carbonate chemistry may occur laterally towards a deposit or within footwall strata. To determine if any such halos could be identified in the Erayinia NW area, the core from all five drillholes were scanned using the Hylogger™ system at the Geological Survey of Western Australia’s (GSWA) core library in Perth. Core were scanned using both the shortwave infrared (SWIR) and thermal infrared (TIR) spectrometers, with data analysed using The Spectral Geologist software. This program compares the spectra produced every ~8 mm of core with a database of known minerals and their characteristic absorption features (as described in Hancock et al., 2013; Duurring et al., 2016). For every spectra produced, the three main minerals contributing to its signature are identified in the TIR and two from the SWIR (Duurring et al., 2016). Summary plots are produced by averaging these over larger (1-3 m) intervals, depending on drillhole depth.

Chlorite, white mica and carbonate chemistry was determined by shifts in the wavelengths of absorption features at ~2250 nm (chlorite, Fe-OH), ~2200 nm (white mica, Al-OH) and ~11,300 nm (carbonate) using The Spectral Geologist. Shifts of these wavelength absorption features to higher values are associated with higher Fe/Mg ratios in chlorite and increasingly Al-poor white mica compositions (McLeod et al., 1987; Herrmann et al., 2001; Guilliamse, 2014; Duurring et al., 2016; Laakso et al., 2016). Specific types of carbonates may be recognized by absorption features at ~11,300 nm and ~14,000 nm (Green and Schodlok, 2016). We used the ~11,300 nm band, assigning carbonate compositions at the following wavelengths: ~11,060 nm (magnesite), ~11,190 nm (dolomite), ~11,250 nm (ankerite), ~11,325 nm (calcite), ~11,390 (siderite) and ~11,419 nm (rhodochrosite).

3.3. Soil geochemistry

In 2015, 794 soil samples were collected during regional soil surveys over the Erayinia NW (n = 364), King (n = 106), and King North (n = 205), and extended (n = 119) Black Raven Mining licence areas (Fig. 6). This was primarily to establish if any geochemical anomalies are present over the King Zn deposit, and identify targets for regional exploration based on similar signatures elsewhere. In 2016 this was complemented by a further 396 samples to infill and further extend the coverage. Soils samples collected during 2015 from Erayinia NW were made on a grid of 100 m north by 50 m east, with 2016 sampling extending the soil grid to the NW on a wider spacing of 400 m north and 100 m east. Samples from King were collected on a spacing of 200 m north and 100 m east.

The sample collection method involved the clearing of organic matter from the 1 m sq. of surface at the target location, and stripping off the top 2-3 cm of possible eolian contamination. Soil material was collected by digging out the underlying material of 30 cm by 30 cm to 20 cm depth. The collected materials were sieved first to < 0.25 mm, then to < 250 μm. Approximately ~200 g of material was dried and retained. Digging tools and sieves were selected to be free of metals of interest.

An orientation study was undertaken by Black Raven Mining (2015) prior to extensive sampling of the 250–150 μm, 150–100 μm, 100–75 μm and < 75 μm fractions. Analysis of the < 75 μm fraction was shown to be the most sensitive for a number of elements (including Cu, Zn and Au), so was selected to be the standard method employed across the tenements (Black Raven Mining, 2016). All < 75 μm fractions of soil samples were subsequently analysed by ALS laboratories, Perth, for gold and multi-element analysis by aqua regia digest and ICP-MS finish. Elements analysed and their detection limits are listed in Table 1.

3.4. U–Pb zircon geochronology

Several large ~10 kg samples were collected from diamond drillcore for U–Pb zircon SHRIMP geochronology from the Erayinia NW area. One additional sample was collected from the King footwall felsic. Approximately 2–3 kg of least-altered sample was processed for zircon separation (see Supplementary Information). Only three samples yielded sufficient zircon for U–Pb geochronology – all from drillhole ECI54D (Fig. 4): SPHGE03, intermediate volcanioclastic rock; SPHGE06, quartz monzonite; SPHGE08, quartz feldspar porphyry.

Zircons were hand-picked and mounted on 25 mm diameter epoxy-resin mounts with chips of M257 zircon (main U/Pb calibration standard, 561.3 Ma, 840 ppm 238U; Nasdala et al., 2008), NBS610 glass, OGC-1 (Pilbara granite zircons, 207Pb/206Pb age 3465 Ma, equivalent to OGl of Stern et al. 2009) and TEMORA (417 Ma; Black et al., 2003). Isotopic analyses were performed on the SHRIMP II instrument at the John de Laeter Centre of Mass Spectrometry at Curtin University, following the procedures outlined by Wingate et al. (2010). Further detail is provided as Supplementary Information. Only the data for SPHGE03 is discussed below, as we consider this the only reliable age. Zircons from intrusive rocks showed evidence for Pb loss and the interpretation of the data is not clear.

4. Results

4.1. Immobile element geochemistry

The mobility of most of the major and trace elements during hydrothermal alteration is well established in the literature (e.g. MacLean, 1990; Jenner, 1996). Only the following elements, that are demonstrably immobile during both hydrothermal alteration and greenschist facies metamorphism should be used to infer protolith affinity: Al2O3, TiO2, Th, Co, Cr, V, the High Field Strength Elements (HFSE; e.g. Nb, Y, Sc, Hf, Zr) and Rare Earth Elements (REE; minus Eu ± Ce) (Pearce and Cann, 1973; MacLean, 1990; Jenner, 1996). Some mobility of the LREE elements may occur within intensely chlorite-altered footwall strata directly underlying massive sulfides (Barrett and MacLean, 1994). The immobile element geochemistry of the Erayinia NW area is presented in Figs. 7 and 8.

All units of amphibolite analysed are of subalkaline affinity (Fig. 7a), with Co and Th concentrations typical of calc-alkaline basalts (Fig. 7d). Co concentrations are significantly lower than footwall amphibolites from King (84–119 ppm), but are more similar to amphibolites from the interpreted hanging-wall (30–49 ppm) (Hollis et al., 2019). Mafic rocks from Erayinia NW plot near the composition of E-MORB on the Nb/Y vs. Th/Yb classification plot of Pearce (2014), just off the mantle array with elevated Th/Yb ratios (Fig. 7g). These geochemical signatures are consistent with the crustal contamination of...
Fig. 7. Immobile element geochemistry for samples analysed from Erayinia NW (fusion method only). (a-c) Zr/TiO₂ vs. Nb/Y discrimination diagrams for volcanic rocks (after Pearce, 1996). Probability ellipses for various rock types are shown. These represent 10% probability contours – that is 10% of samples from that group will plot outside the respective contour. (d) Th vs. Co discrimination diagram of Hastie et al. (2007). (e-f) VHMS fertility diagrams of Lesher et al. (1986); Fig. 7e) and Hart et al. (2004); Fig. 7f). The fields for felsic rocks from Teutonic Bore and King are also shown (from Hollis et al., 2019; unpublished). (g) Th/Yb vs. Nb/Yb diagram of Pearce (2008, 2014). Arc-related volcanic rocks will parallel the mantle array, whereas samples trending obliquely to it are associated with crustal contamination (Pearce, 2008), 1, Yilgarn Felsic Intrusion (Hayman et al., 2015b), 2, Felsic Archaean crust (Rudnick and Fountain, 1995), 3, Upper Continental Crust (Taylor and McLennan, 1985).
plume derived basalts, common across the Eastern Goldfield Super-
terrane (Barnes et al., 2012; Smithies et al., 2018). Chondrite-normal-
ized REE profiles are gently dipping (Fig. 8d-g), with the Zn-bearing
coherent mafic flow from drillhole EC157D displaying a slightly flatter
profile and lower Zr/TiO₂ ratio.

Intermediate volcaniclastic rocks from Erayinia NW are character-
ized by Th and Co concentrations typical of calc-alkaline andesites
(Fig. 7d). All samples plot within the andesite field of Pearce (1996;
Fig. 7b). Chondrite-normalized REE profiles are similar to calc-alkaline
andesites from Teutonic Bore, King (Fig. 8h), and across the Eastern
Goldfields Superterrane (Barnes and Van Kranendonk, 2014).

Quartz-sericite altered felsic rocks from Erayinia NW plot within the
andesite and dacite fields of Pearce (1996; Fig. 7b). These rocks have FI
to FII geochemical characteristics (Fig. 7e-f; after Lesher et al., 1986),
moderately high Zr/Y ratios and low HFSE enrichment. Both the felsic
rocks from Erayinia NW and King display similar REE profiles, although
the former have slightly flatter HREE profiles (Fig. 8i). HFSE con-
centrations are significantly lower than felsic rocks at Teutonic
Bore (Fig. 8e-f) and other VHMS deposits of the Yilgarn Craton ex-
cluding Nimbus (Hollis et al., 2015a, 2017a, 2017b). Rare earth ele-
ment profiles are also similar to those from the interbedded black shales
(Fig. 8b).

All intrusive rocks from the Erayinia NW area display steep chon-
drite-normalized REE profiles (Fig. 8a), and have very high Zr/Y and
La/Yb ratios (Fig. 7c) regardless of composition. These profiles are sim-
ilar to those from quartz-feldspar porphyry intrusions cutting both the
footwall and hanging-wall of the King deposit (Fig. 8a). HFSE con-
centrations are low (e.g. < 3.8 ppm Nb), and these granitic rocks are
geochemically most similar to the High-Ca group of granitoids from the
Yilgarn Craton constrained to c. 2680–2660 Ma (see discussion).

4.2. Mobile element geochemistry

The mobile element geochemistry of rocks analysed from the
Erayinia NW area is displayed in Figs. 9 to 12. Significant correlations
between a number of major elements (e.g. Si, Na, K, Fe, Ca, Mg, Mn)
and trace elements (e.g. Ba, Rb, Sr, Sb, Tl) that are readily mobilised by
hydrothermal fluids are shown in Fig. 9. Strong positive correlations
occur in mineralized mafic to felsic volcanic/volcaniclastic rocks and
black shales between the following VHMS pathfinder elements: Ag, As,
Bi, Cd, Cu, Eu/Eu*, Mo, Pb, Sb, Sn, Te, Tl, Zn (Pearsons correlation
coefficient, r², between each element ~0.77 to 0.91). Anomalously high
concentrations of base metal and pathfinder elements from Erayinia NW occur in black
shales (Fig. 9).

Sodium depletion is one of the most widely-recognized and robust
geochemical halos for VHMS deposits worldwide (Date et al., 1983;
Galley et al., 1995; Piercey, 2009). A strong negative correlation be-
tween K₂O and Na₂O (also CaO) can be expected due to the ser-
icitization of feldspar (Piercey, 2009; Fig. 11 - see discussion). Further
dilution of Na can occur through large mass gains of elements such as
Si, K, Mg, S and Fe (MacLean, 1990). Of the northernmost drillholes
(EC156D to EC154D), the Na concentration of felsic rocks appears to
decrease southwards. Na-depletion is most pronounced in felsic rocks in
hole EC154D (0.8–1.7 Na₂O wt%) and higher Na₂O concentrations to
the north (1.8–2.3 wt% in EC155D, 2.3–4.5 wt% in EC156D) corre-
spond to reduced sericitization as noted in the drillcore. No such

Fig. 8. Chondrite-normalized REE profiles (after McDonough and Sun, 1995) for samples analysed herein from Erayinia NW. Shaded fields are also shown for rocks from Nimbus, King and Teutonic Bore (Hollis et al., 2017a, 2017b, 2019; Hollis, unpublished).
systematic changes occur with respect to SiO$_2$, MgO, CaO or Fe$_2$O$_3$. Local elevations in these elements correspond to increased amounts of quartz, chlorite, carbonate and pyrite noted in drillcore.

Volcanic rocks surrounding massive pyrite in the southernmost holes EC157D and EC158D display low SiO$_2$ (51.6–60 wt%), and variable Na$_2$O (1.6–5.9 wt%), K$_2$O (0.4–3.8 wt%), MgO (~4 wt%) and Fe$_2$O$_3$ (6.4–10.8 wt%). Zinc concentrations range from 132 to 544 ppm, with slightly elevated levels of associated trace elements (< 0.3 ppm Sb, < 1.2 ppm Tl, < 0.1 ppm Hg and Bi, < 3 ppm Mo, < 5.5 ppm As). A thin coherent mafic flow underlying massive sulfides in drillhole EC157D contains stringer sphalerite (0.19% Zn over 4 m). This sample is characterized by similar major element concentrations, and low abundances of trace elements (e.g. 1.4 ppm As, 0.2 ppm Sb, 0.2 ppm Tl).

As trace elements are highest in black shales (Fig. 9), including elements typically associated with VHMS deposits worldwide (e.g. Sb, Tl), box and whisker diagrams of black shale geochemistry are shown in Fig. 12. These plots include data from fusion lithogeochemistry, four-acid digest and pXRF geochemistry (where the element is available). Moving south from hole EC156D, maximum, mean and median concentrations of base metals (Zn, Cu, Pb) and a number of...
Prominent EC154D and EC157D. Aluminium-normalized ratios in black shales (i.e. concentrations show the opposite pattern, decreasing towards holes those obtained from a sample of graphitic pelite at the ore horizon from values of all these elements. Mean concentrations are comparable to and EC157D. The most southerly hole drilled (EC158D) shows reduced 

Supplementary Fig. 1. In these three drillholes, intermediate and ma siderite and ankerite. Signi abundances (generally Al-rich muscovite) are low in intermediate and felsic rocks chlorite is signi

lithologies are characterized by high abundances of Fe especially in drillhole EC154D. Fe-rich chlorite is restricted to the felsic rocks chlorite is signi

particularly in drillhole EC154D). Fe-rich chlorite is restricted to the

massive pyrite (~57 m) and stringer sphalerite (~120 m) in chloritized mafic rocks, with FeMg chlorite present at depth. White mica abund ance is high in felsic and intermediate rocks, and low in mafic rocks, showing a range of compositions (from Al-rich to Al-poor). Immediately below massive pyrite mineralization white mica compositions are characterized by muscovite, whereas phengite and paragonite are more common at depth. Where present, carbonate alteration is typically dominated by siderite and ankerite (with minor calcite present at depth).

4.4. Soil geochemistry

Soil geochemistry (< 75 μm fraction) was extremely effective at highlighting the position of the King Zn deposit (Fig. 15). Zn, Pb and Cu concentrations are highest directly over the centre of the orebody (to 1208 ppm Zn, 314 ppm Cu, 134 ppm Pb; Supplementary Fig. 2) consistent with known sulphide phases identified in drill core (i.e. sphalerite > chalcopyrite > galena). Zn-associated elements form a broad multi-element geochemical anomaly: Ag (to 490 ppb), Au (to 34 ppb), Bi (to 1.2 ppm), Cd (to 6.2 ppm), Mo (to 2.69 ppm), Sb (to 1.55 ppm), W (to 2.63 ppm) as shown in Supplementary Fig. 2. Hg, Tl, Se and Sn concentrations are locally elevated over the orebody but are not systematic. Interestingly, Au and Ag concentrations are highest immediately to the north of King outside the area of diamond drilling. Pearson correlation pairs for Zn are highest for Pb and Cd (r2 > 0.96), with weaker correlations (r2 0.57–0.68) to Ag, Cu, Sc and W. Au is strongly correlated with Ag (r2 0.87), Cd and Cu (r2 0.7). As, Mo, Sb, Se and Tl are poorly correlated with all other trace elements (r2 < 0.5). However, some of these elements show stronger correlations in log-space (e.g. Mo–W).

Principle component analysis (classical, with no data trim) was also performed using the main suite of anomalous trace elements - Ag, As, Bi, Cd, Cu, Mo, Pb, Sb, Sc, Se, Tl, W, Zn – following transformation of the data using centred log-ratios. Au, Te and Hg were not used due to the low detection limits. The first four principle components (PC1 to PC4) have eigenvalues above 1 or > 10% control of the data. Together they represent 77.8% of all variation. The remaining components (PC5
to PC2) each control 5 to 1% of the data. A large geochemical bullseye over the King deposit is revealed by PC1 and PC3 (see Supplementary Fig. 2). PC1 is strongly controlled by Zn-W-Ag-Cu in positive space, whereas PC3 is controlled by Mo-Bi-W in positive space. On a plot of PC1 and PC2, four main elemental clusters are apparent Zn-Cu-Ag-Cd, W, Mo, Sb, As, and Pb-Bi-Sc-Se-Tl.

Although soil samples from King are underlain predominantly by residual outcrop and colluvium, the rest of the greenstone belt is host to a variety of regolith types (Figs. 6, 15). Therefore, regional soil samples were classified by underlying regolith type according to Jones (2007) to investigate any dampening effects on elements of interest. Soil geochemical data for black shales has been removed. The Box Plot uses two indices of alteration – the Alteration Index (AI) and Chlorite-Carbonate-Pyrite Index (CCPI). See text for definitions.

$$AI = \frac{100(K_2O + MgO)}{(K_2O + MgO + Na_2O + CaO)};$$

$$CCPI = \frac{100(MgO + FeO)}{(MgO + FeO + Na_2O + K_2O)}$$

Fig. 11. Box Plots after Large et al. (2001a) showing common major element geochemical trends associated with VHMS mineralization at Erayinia NW, King (Hollis et al., 2019, unpublished), Teutonic Bore (Hollis unpublished) and Nimbus (Hollis et al., 2017a, 2017b). Geochemical data for black shales has been removed. The Box Plot uses two indices of alteration – the Alteration Index (AI) and Chlorite-Carbonate-Pyrite Index (CCPI). See text for definitions.
geochemical anomalies have been identified, one due to high Th/U, and two metamict grains that yielded discordance (> 10%), four due to evidence for Pb-loss, data for selected elements is shown in Fig. 17. Several multi-element analyses on twenty-eight grains were performed on zircons from sample SPHEGEO3 - an intermediate volcanioclastic rock from drillhole EC154D (Fig. 4). Fifteen analyses were removed; seven were removed due to high discordance (> 10%), four due to evidence for Pb-loss, one due to high Th/U, and two metamict grains that yielded 207Pb/206Pb ages of ~2635 Ma. Grain 9 was also removed as it gave a young 207Pb/206Pb age of c. 560 Ma and is interpreted as reset. From the remaining twenty grains, eighteen were included in the final age. All are < 10% discordant. These yielded an age of 2685 ± 5 Ma (MSWD 1.4; Fig. 18) which is interpreted as a magmatic age for the volcanic rocks of the Erayinia NW area. The two additional grains (25–1 and 22–1), gave inherited ages of ca. 2733 Ma and 2766 Ma. Our new age of 2685 ± 5 Ma is consistent with previous geochronology in the area, which yielded an igneous crystallization age of 2680 ± 5 Ma (Wingate and Bodorkos, 2007b). Inherited grains > 2.7 Ga are consistent with the presence of c. 2.77–2.72 Ga basement under the Gindalbie age volcanic rocks in the Eastern Goldfields (Czarnota et al., 2010).

5. Discussion

5.1. A tectonic-stratigraphic framework for mineralization

Despite the increased metamorphic grade and degree of deformation at King, broad comparisons can be made to the stratigraphy described here from Erayinia NW. In both areas a consistent geochemical evolution is apparent from a thick sequence of calc-alkaline basalt through intermediate volcanioclastic rocks, to felsic and graphitic argillaceous rocks. A return to mafic lithologies in both areas occurs in the hanging-wall to the mineralized felsic sequence (Fig. 3). Felsic rocks in both areas are largely of FI (to FII) affinity (Fig. 7e-f) indicative of deep crustal melting and reduced VHMS prospectivity (Lesher et al., 1986; Hart et al., 2004). However, at King, VHMS prospective FIII-affinity felsic rocks have recently been recognized along strike associated with Zn-Cu-Au mineralization (King North prospect; Fig. 6) and in the hanging-wall of the King Zn deposit (Kelly (2018). VHMS prospective FIII-affinity felsic rocks may exist in the Erayinia NW area and remain a high priority target for exploration. It is likely that both sequences were deposited in a deep marine, rifted-cratonic setting (either plume and/or subduction related; see Hollis et al., 2019).

Perhaps the most significant geochemical differences between the two areas are reflected in the immobile element characteristics of the mafic rocks. Footwall amphibolites from King having considerably higher Co concentrations and plot in different fields on a range of tectonic discrimination diagrams (not shown). Although a number of workers have highlighted the problem with using such diagrams for classifying the tectonic setting of Archaean rocks (e.g. Bédard et al., 2013; Hollis et al., 2017a), they are still useful to highlight differences in immobile element ratios. Whereas samples from the Erayinia NW area plot predominantly in the ‘late to post-orogenic intra-continental’ field of Cabanis and Lecolle (1989) and ‘calc-alkaline basalt’ field of Pearce and Cann (1973), the King amphibolites plot in the ‘back-arc’ and ‘MORB/island-arc tholeiitic’ fields respectively. Thus, the King amphibolites more closely resemble 2.7 Ga Lunnon plume-head lavas (Barnes et al., 2012) and mafic rocks associated with the c. 2705 Ma Nimbus deposit (Hollis et al., 2017a), whereas metabasalts from Erayinia NW are more similar to the younger Gindalbie age basaltic rocks (c. 2690–2680 Ma) such as those from Teutonic Bore and Jaguar (Belford et al., 2015). This finding is consistent with existing age constraints from the two areas. Whereas the Erayinia NW stratigraphy has been constrained to c. 2685–2680 Ma through our new and existing U–Pb zircon geochronology (Fig. 18), the King stratigraphy (east of the Claypan Fault) is considered to be older (c. 2705–2690 Ma?; Fig. 3) due to the presence of tecto-schists (likely metamorphosed ultramafic rocks) and thin units of BIF in the local stratigraphy (Hollis et al., 2019). It is likely that the Erayinia NW area represents a similar volcanic sequence to that at King, but a younger volcanic cycle much higher in the stratigraphy. These two volcanic cycles were juxtaposed by movement on the Claypan Fault.

Analysis was unsuccessful.

Whereas some elements in soils are little affected by underlying regolith type (e.g. Bi, Tl, Pb), it is clear that others elements are. Ca, Fe, Cu, Sb and As concentrations are considerably higher in soils over areas of outcrop and colluvium, than playa lakes and sand plains (Fig. 16). This is further highlighted by variations in the Chemical Index of Weathering (Fig. 16). To overcome these artefacts, and obtain a consistent base level for the region, soil data was levelled for each element by regolith type using Z-score (also known as standard score). Gridded data for selected elements is shown in Fig. 17. Several multi-element geochemical anomalies have been identified which are discussed in Section 5.4.

4.5. U–Pb zircon geochronology

Fig. 12. Tukey Box Plots of trace elements in black shales at Erayinia NW. Numbers within boxes refer to the number of samples included in each group.
Fig. 13. Shortwave infrared chlorite and white mica hyperspectral data from the northernmost diamond drillholes at Erayinia NW (EC156D, EC155D and EC154D). Data from intrusive rocks have been removed for clarity (see Supplementary Fig. 1 for full profiles).
The position and repeated occurrence of VHMS mineralization at different times in the Erayinia region is perhaps not surprising. Several episodes of VHMS mineralization have been recognized throughout the history of the Yilgarn Craton, which are predominantly restricted to two main zones of juvenile crust - the Cue Zone of the Youanmi Terrane and Kurnalpi Zone of the Eastern Goldfields – as revealed by regional Sm–Nd and Pb isotope variations (Huston et al., 2014; Hollis et al., 2015a). These areas have been interpreted to reflect long-lived Archaean paleo-rift zones into which plume magmatism was repeatedly focussed (Ivanic et al., 2010; Huston et al., 2014).

In the Cue Zone of the Youanmi Terrane, at least four distinct periods of VHMS mineralization have been recognized at > 2.95 Ga (e.g. Golden Grove, Ravensthorpe), c. 2815 Ma (Yaloginda Formation and Kantie Murdana Volcanics Member), c. 2750 Ma (Greensleeves Depth (m)), c. 2650 Ma (Kuralpi Zone of the Eastern Goldfields – as revealed by regional Sm–Nd and Pb isotope variations). These areas have been interpreted to reflect long-lived Archaean paleo-rift zones into which plume magmatism was repeatedly focussed (Ivanic et al., 2010; Huston et al., 2014).

Fig. 14. Geochemical and hyperspectral data from diamond drillhole EC157D. SWIR, short wave infrared; TIR, thermal infrared.
Fig. 15. Selected soil geochemistry of samples analysed from King, Erayinia NW, King North and surrounding areas. The position of diamond drillholes, and more recent RC drilling at King North, is shown. Regolith classification is after Jones (2007).

Fig. 16. Split probability plots for soil samples classified according to underlying regolith type. The most significant variations are apparent in Ca, As, Sb, Cu – with soils developed over sand plains and playa lakes showing the most depleted concentrations. Concentrations of Zn and Pb are typically elevated when soils are developed over outcrop or colluvium.
Intermediate volcanic rocks of the Erayinia NW area. The data yield a 207Pb/206Pb age of 2685 ± 5 Ma (MSWD 1.4) which is interpreted as a magmatic age for the intermediate volcaniclastic rock. The data point error ellipses are 2σ.

Deep-seated crustal structures at the margins of the rift-zone may have facilitated VHMS mineralization over extended periods of time.

Late intrusive activity in both the King and Erayinia NW areas is similar and dominated by large intrusions of quartz monzonite, granodiorite, and sills of quartz-feldspar porphyry. At King this predominantly occurs in the stratigraphic hanging-wall of mineralization, but is common throughout the Erayinia NW stratigraphy (Fig. 5).

Whereas the King stratigraphy was metamorphosed to lower amphibolite grade due to the proximity of a large intrusion (Fig. 3), rocks at Erayinia NW remained largely unaffected by late granite emplacement. Building on the work of Champion and Sheraton (1993, 1997), Champion and Cassidy (2000) conducted an extensive geochemical study of granitic intrusive rocks from across the Yilgarn Craton. Five broad groups were recognized: High-Ca, Low-Ca, High-HFSE, Mafic and Syenitic (also see Czarnota et al., 2010). Based on low Th (7.5–11.2 ppm) and HFSE concentrations, moderate SiO2 (~70 wt%) and moderately low K2O (2.5–4.2 wt%) the intrusive rocks from Erayinia NW and King are both geochemically consistent with the High-Ca group of granitoids from the Yilgarn Craton constrained to c. 2680–2660 Ma. These ages are consistent with new SHRIMP U–Pb zircon geochronology on intrusive rocks in drillhole EC154D (presented as Supplementary Material).

Champion and Cassidy (2000) discussed the close temporal and spatial relationship between high-HFSE granitoid intrusions and VHMS mineralization across the Yilgarn Craton. Such intrusions have not been identified in the Erayinia/King region, but remain a target for exploration.

5.2. Geochemical vectors to mineralization

Diamond drilling at Erayinia NW has identified widespread hydrothermal alteration across a strike length exceeding 3 km, with significant intercepts of base metals in a number of holes (e.g. EC155D 19 m at 0.4% Zn; EC157D 4 m at 0.19% Zn). Extensive but weak quartz-sericite ± pyrite alteration is predominantly restricted to the sequence of felsic volcanic/volcaniclastic rocks interbedded with metal-bearing, variably graphitic, black shales. More intense zones of local chloritization occur in mafic rocks in the southern part of the sequence.
Samples analysed are characterized by highly variable concentrations of major and trace elements, with trends typical of hydrothermally altered volcanic rocks associated with modern and ancient VHMS systems (e.g., Large et al., 2001a, 2001b; Galley et al., 2007; Hollis et al., 2014; Yeats et al., 2017). Anomalously high concentrations of Na are present in weakly altered rocks, and those associated with regional semi-conformable alteration (i.e. Na-gains) (Piercey, 2009). Data from Erayinia NW plot predominantly in the fresh to weakly altered semi-conformable alteration (i.e. Na-gains) (Piercey, 2009). Relic volcanic textures are apparent in many of the altered rocks (e.g. quartz and feldspar phenocrysts) and few samples are characterized by high Sb, Ti, Ba/Sr or Hg/Na2O typical of rocks from the footwall of VHMS deposits worldwide (Fig. 9).

The Al2O3/Na2O vs. Na2O diagram of Spitz and Darling (1978), and the K2O + Na2O vs. 100%K2O/K2O + Na2O diagram of Hughes (1973) are useful for discriminating pipe-like discordant alteration (i.e. Na-loss) from weakly-altered rocks, and those associated with regional semi-conformable alteration (i.e. Na-gains) (Piercey, 2009). Data from Erayinia NW plot predominantly in the fresh to weakly altered field, with few samples (excluding black shales) showing significant Na-loss (Fig. 9). The Na concentrations and K/Na + K ratios are typical of distal ‘quartz-sericite’ alteration surrounding VHMS deposits (Date et al., 1983; Piercey, 2009; Hollis et al., 2014). Hydrothermal up-flow zones are typically marked by significantly lower Na concentrations in felsic volcanic rocks (i.e. < 0.4 wt% Na2O; Date et al., 1983). Molar element ratio plots (e.g. K/Al vs. (2Ca + Na + K)/Al; Si/Al vs. (Na + K)/Al) show similar very weak trends towards the muscovite-sericite and chlorite mineral nodes typical of distal hydrothermal alteration (Supplementary Fig. 5).

The Box Plot of Large et al. (2001a) also provides a useful tool for deconstructing major element variations associated with VHMS deposits. It combines two alteration indices – the Alteration Index (AI; after Ishikawa et al. 1976) and Chlorite-Carbonate-Pyrite Index (CCPI) (Fig. 11). Whereas AI records the replacement of volcanic glass and feldspar by sericite and/or chlorite, CCPI reflects increased Mg–Fe enrichment due to chlorite, carbonate and pyrite within the inner parts of alteration pipes (Large et al., 2001a). Although neither of these indices include SiO2, this diagram still allows common alteration trends to be distinguished. For example, distal hydrothermal alteration associated with VHMS deposits in felsic volcanic rocks is typified by trend 1 (Fig. 11) towards the sericite mineral node. With increased proximity towards chloritic feeder zones that often underlie massive sulfide mineralization, hydrothermal alteration is characterized by trends 2 (sericite-chlorite-pyrite) and 3 (chlorite-pyrite ~ sericite) (Large et al., 2011a). Immediately adjacent to massive sulfides, samples plot high CCPI with variable Al (i.e. trend 4; chlorite-carbonate) (Large et al., 2011a). Immediate hanging-wall alteration is often characterized by trend 5 (carbonate-sericite alteration).

Data from the King, Teutonic Bore and Nimbus deposits of the Eastern Goldfields are shown in Fig. 11 for comparison. At King, the diagonal trend 3 characteristic of a feeder zone occurs for samples of cordierite and/or anthophyllite bearing banded schist (Fig. 11a). Samples from the quartz-chlorite ± magnetite schists at King (Fig. 11a) are geochemically similar to closely associated footwall chlorite-carbonate alteration. Unsurprisingly, talc-schists that contain clots of specular hematite from King plot near the Mg–Fe ore corner (characterized by highest CCPI and AI; Fig. 11a). Samples from Teutonic Bore, directly underlying massive sulfides, also plot near the ore corner whereas those from the hanging-wall of the deposit and post-mineralization intrusive dolerites are ‘least altered’ (Fig. 11b). At Nimbus, felsic rocks cluster in the least altered rhyolite field, with more intensely altered units dominated by trends towards both the ore corner and sericite mineral node (Fig. 11c). Mafic rocks at Nimbus are characterized by trends reflecting an increased abundance of chlorite and/ or carbonate (Fig. 11d).

Samples analysed from Erayinia NW fall predominantly in the ‘least altered’ field of the Box Plot with considerable scatter (Fig. 11a). Only a handful of samples from holes EC157D and EC158D appear to show a poorly defined diagonal trend towards the direction of the ore corner. This is consistent with chlorite-pyrite-sericite alteration (trend 3; Fig. 11a) surrounding lenses of massive pyrite and stringer sphalerite, weak quartz-sericite ± pyrite alteration in felsic rocks, and minimal alteration elsewhere (e.g. drillhole EC156D). Due to the intensity of hydrothermal alteration, drillhole EC157D is believed to represent the most VHMS prospective section of the Erayinia NW stratigraphy drilled to date. VHMS mineralization at Erayinia NW is most likely to be associated with a synvolcanic fault, in a volcanic vent proximal setting, associated with an FIII-affinity rhyolite dome. This may occur down-dip or along strike of the massive pyrite intersected in drillholes EC157D and EC158D.

Several other broad geochemical halos can also serve as indicators to VHMS systems and hydrothermal alteration. These include anomalously high Sb and Ti concentrations (Large et al., 2001b; Piercey, 2009), the presence of positive Eu anomalies (Sverjensky, 1984), and abundance of normative corundum from CIPW calculations (Grunsky, 2013; Hollis et al., 2019). Building on previous research, Large et al. (2001b) discussed Sb and Ti halos surrounding a number of Australian VHMS deposits. Both the Rosebery and Hellyer deposits exhibit concentrations of Sb and Ti exceeding 1 ppm, extending several hundred metres in the hanging-wall of massive sulfides. Higher values (> 10 ppm) are common closer to ores, with values decreasing away from mineralization (Large et al., 2001b). Data from Erayinia NW show weak enrichments in Sb and Ti in hydrothermally altered felsic volcanic rocks and interbedded black shales (Fig. 10b). Concentrations of both elements are erratic in this sequence, but are considerably higher than in surrounding metabasalts and least altered felsic rocks from drillhole EC156D (Figs. 9, 10b).

As Eu is readily liberated during hydrothermal alteration, associated with the breakdown of feldspar at temperatures > 250 °C (Sverjensky, 1984), prominent positive Eu anomalies are a strong indicator of high temperature hydrothermal alteration. Again Eu/Eu* values are erratic throughout the five drillholes, but are generally higher in hydrothermally felsic rocks, black shales, and chloritized rocks surrounding massive pyrite in hole EC157D (Fig. 10a).

The abundance of normative corundum from CIPW normative mineralogy calculations is a useful guide to the extent of alkali leaching in hydrothermally-altered sequences (Grunsky, 2013). At King, Hollis et al. (2019) noted that values were highest in feeder zone quartz-chlorite schists and the immediate footwall of massive sulfide mineralization. By contrast, a lack of alkali leaching in the hanging-wall was associated with values of 0. High values of normative corundum at Erayinia NW again occur in altered felsic rocks, black shales, and chloritized rocks surrounding massive pyrite (Fig. 10a).

Although black shales at Erayinia NW are variable in their metal contents, maximum and mean concentrations in each hole are useful vectors to mineralization. Increasing values of pathfinder elements (including: Ag, As, Bi, Cd, In, Mo, Ni, Sb, Sn, Te, Ti; plus Alteration Index and K2O; Fig. 12) and lower Al, Ba, Sr in black shales towards holes EC154D and EC157D further suggest this area is most proximal to the main site of hydrothermal up-flow. Maximum concentrations of each element are similar to graphicith schists from the ore horizon at King (Fig. 12).

The intercept of massive pyrite in the two southernmost drillholes (~300 m apart) is also an encouraging sign that this area may be proximal to zones of polymetallic sulfides. Units of barren massive pyrite are common feature of VHMS deposits worldwide, often representing more distal and lower temperature sites of sulfide precipitation, and/or forming early in the life of the deposit. At Nimbus, myriad lenses of barren massive pyrite (~2 to 7 m thick) occur directly above discordant zones of polymetallic sulfide mineralization (Hollis et al., 2011a).
et al., 2017a). Early units of massive pyrite helped to seal the hydrothermal system from seawater, with later fluids dominated by magmatic geochemical and isotopic signatures (Caruso et al., 2018). In the Teutonic Bore camp (Fig. 1), pyritic lenses occur within ~100 m of the Bentley deposit. Polymetallic massive sulfide lenses also typically grade out to pyrite dominant zones at their edges at each of the deposits. Lenses of barren massive pyrite are also commonly found in the Youanmi Terrane. For example, in the c. 2.72 Ga Gum Creek greenstone belt (Fig. 1), two 8 m thick units of massive pyrite were drilled within a sequence of carbonaceous shales and volcanic rocks at Blind Bat (Gateway Mining, 2014). The underlying zone is marked by Na depletion (from ~1 to < 0.5 wt% Na), K gain (to 2.5 wt% K) and VHMS trace element (Zn-Cu-Sb-Ti-Te-W-Mo-Se) enrichments (Hollis unpublished).

5.3. Hyperspectral vectors to mineralization

Myriad researchers have investigated Mg and Fe variations in chlorite from VHMS deposits worldwide (summarised by Piercey, 2009; Shanks, 2012). Systematic changes in Fe/(Fe + Mg) ratios with proximity to ore, coupled with advances in hyperspectral analysis (e.g. handheld techniques, satellite imagery), can provide rapid and cost-effective vectors to mineral deposits. In VHMS deposits where the inner parts of the feeder systems are effectively sealed from seawater, Fe/(Fe + Mg) ratios of chlorite typically increase towards the core of the main feeder zone, with low ratios restricted to the margins of the system (Piercey, 2009; Shanks, 2012). In these instances, the core of the feeder zone is dominated by an undiluted hydrothermal end member and Fe-rich chlorite is dominant (Shanks, 2012). Examples include: the Kuroko deposits of Japan; Horne and Matagami deposits of the Abitibi greenstone belt; Brunswick No. 12, Caribou, Halfmile Lake and Heath Steele deposits of the Bathurst Mining Camp, Canada; and the Hercules deposit of Australia (references in Dehnavi et al., 2019 and Piercey, 2009).

However, a number of deposits worldwide show the opposite pattern, with decreasing Fe/(Fe + Mg) ratios towards the core of the footwall alteration system. These include the Seneca, Southbay and Corbet deposits of Canada, and the Hellyer, Thalanga and Quinns deposits of Australia (references in Dehnavi et al., 2019; Duuring et al., 2016). In these instances, seawater was entrained into the core of the feeder zone and the resultant chlorite is Mg-rich (Shanks, 2012). The Iheya North hydrothermal field of the Okinawa Trough, Japan, provides a modern example where Mg-rich chlorite compositions are dominant even in the main feeder zone (Yeats et al., 2017).

Regional background signatures at Erayinia NW are dominated by FeMg chlorite, particularly in ‘least altered’ mafic and intermediate rocks (Fig. 13). By contrast, quartz-sericite altered felsic volcanic rocks are characterized more Mg-rich chlorite compositions particularly in drillholes EC154D and EC157D when associated with mineralization and more intense hydrothermal alteration (Fig. 13). In drillhole EC157D, chlorite compositions are extremely Mg-rich surrounding units of massive pyrite (~55 m) and stringer sphalerite (~120 m; Fig. 14). As Fe/(Fe + Mg) ratios provide a proxy for temperature (MacLean and Kranidiotis, 1987), the Mg-rich chlorite compositions in drillhole EC157D and lack of significant chloropyrite further indicate that drilling did not intersect the core of the feeder zone. Chlorite associated with sphalerite rich ore will often have lower Fe/Fe + Mg ratios than chloropyrite-rich samples (e.g. McLeod and Stanton, 1984) as high temperatures (> 250°C) are required to transport Cu.

Two main compositional affinities have been recognized for white mica associated with VHMS deposits worldwide. Whereas Ba-rich phengitic (K bearing, Al-poor) white mica occurs near the ore zone of several deposits (e.g. Hellyer, Rosebery, Neves-Corvo), muscovitic (K bearing, Al-rich) white mica has also been documented within inner alteration zones proximal to ore for a number of other deposits (e.g. Mt. Lyell, Western Tharsis, Mt. Windsor) (references in Dehnavi et al., 2019). Although strictly paragonitic compositions (Na bearing, Al-rich) are often rare, as white mica associated with VHMS mineralization is typically Na-poor (Piercey, 2009), slightly sodic muscovite also occurs in a number of deposits (Herrmann et al., 2001). This includes the hanging-wall of the Rosebery deposit and proximal alteration zones at Western Tharsis and Highway-Reward (Herrmann et al., 2001).

In the Panorama area of the Pilbara Craton, Western Australia, several studies have documented large hydrothermal convection cells at the km-scale (e.g. Van Ruitenbeek et al., 2005, 2012; Cudahy, 2016). A number of distinct styles of hydrothermal alteration (e.g. feldspar-sericite-quartz, sericite-quartz, chlorite-quartz) were identified and mapped in the volcanic sequence by Brauhart et al. (1998). Building on this research and subsequent studies, Van Ruitenbeek et al. (2012) linked these alteration styles to hydrothermal convection cells and distinct white mica compositions using airborne hyperspectral imagery. Sites of seawater recharge in the upper crust are characterized by least altered whole rock compositions, low white mica contents, and Al-rich (muscovitic) white mica due to interaction with unevolved seawater (Van Ruitenbeek et al., 2012). Deeper circulation and continued interaction with volcanic rock resulted in Al-poor (phengitic) compositions at depth and zones of intense chlorite-quartz alteration. As the evolved hydrothermal fluids upwelled, discordant zones below VHMS deposits are marked by high to intermediate Al-content white micas in chlorite-quartz dominated alteration zones (Van Ruitenbeek et al., 2012).

At Erayinia NW, drillhole EC156D is as least altered (Figs. 11, 12) and can be interpreted as a regional background signature. White mica abundances are of low abundance in mafic and intermediate rocks, and are restricted to the felsic sequence (Fig. 13). Muscovite, phengite and paragonite all occur, in order of decreasing abundance. Further south in drillhole EC155D white mica is dominated by muscovite with lesser phengite. Within drillhole EC154D white mica is much more abundant, with significant white mica in both felsic and surrounding mafic rocks. In drillhole EC157D zones of massive sulfide and sphalerite mineralization are dominated by Al-rich muscovitic compositions, with phengite at depth in intermediate lithologies. The above is broadly interpreted as an increase in white mica content towards drillhole EC157D and increasingly muscovitic (~2205 nm) compositions towards mineralization. Although the white mica and chlorite may have undergone some degree of recrystallization in response to greenschist facies metamorphism, trace-element studies from the Bathurst Mining Camp have demonstrated that primary hydrothermal signatures at this metamorphic grade are retained (see Dehnavi et al., 2019).

Carbonate associated with VHMS deposits worldwide is typically Fe-Mn-rich, though some deposits are associated with dolomite (Piercey, 2009). In drillholes EC156D and EC155D carbonate is rare, but when present is typically calcite and dolomite (with lesser siderite) in the lower mafic sequence. By contrast in drillhole EC157D carbonate is dominated by siderite [FeCO₃] near massive sulfides, with siderite and ankerite [Ca(Fe,Mg,Mn)(CO₃)₂] present in the footwall of mineralization. No Mn-bearing carbonates were identified at Erayinia NW. Mn-bearing carbonates such as rhodochrosite [MnCO₃] and kutnohorite [CaMn(CO₃)₂], when present in VHMS systems, often occur around ore zones (e.g. Rosebery deposit; Green and Schoedlok, 2016). Again, the hyperspectral characteristics of the core are consistent with drillhole EC157D being the most proximal to a zone of hydrothermal up-flow.

5.4. Soil geochemistry: regional targets

Soil geochemistry using the < 75 μm fraction, levelled by regolith type, has been demonstrated to be an effective guide to mineralization in the Erayinia region (Fig. 17). We consider this a valid and robust approach to evaluate soil geochemistry in new areas of the Eastern Goldfields where regolith patterns are complex, and detailed satellite mapping is not feasible due to thick vegetation cover. As detailed below, many of the identified multi-element geochemical anomalies correspond to positions of known mineralization and VTEM anomalies.
High soil concentrations of Ag, As, Au, Bi, Cd, Cu, Mo, Pb, Sb, Sc, Se, Tl, W and Zn are also consistent with bedrock geochemical anomalies associated with mineralization at King (Hollis et al., 2019), King North (Kelly, 2018), and Erayinia NW (Fig. 9).

West of the Claypan Fault, a large region of unexplained anomalous Zn-(Pb–Tl) occurs north of drillhole EC156D (anomalies 1a,b), and small multi-element geochemical anomalies (Zn-Cu-Pb-Sn-Bi-Mo-As) east of holes EC157D (anomaly 2a) and EC155D (anomaly 2b). Anomaly 2a is also associated with a VTEM target as identified by Black Raven Mining. Additional multi-element (Zn-Cu-Pb-Sn-Bi-W-TI-As) anomalies occur to the west and far south (anomalies 3a,b) of current drilling.

East of the Claypan Fault, a number of strong geochemical anomalies are associated with the King stratigraphy (Fig. 17) – some of which are associated with VTEM targets. These include: King North (Zn-Cu-Pb-Sn-Sb-W; with an associated VTEM target), anomaly 9 SE of the King deposit (Zn-Cu-Pb-Sn-Bi-Tl), anomaly 8 on the eastern limb of the major fold axis (Fig. 2; with VTEM targets in the east); and anomaly 6 south of King (W-Mo-As; with a single VTEM target). Single element Mo and W anomalies may be related to underlying granitic intrusions. Molybdenite mineralization has been identified in a late granitoid intrusive from the King area.

5.5. Targeting VHMS mineralization in Archaean terranes

In Fig. 19 we present a guide for targeting VHMS mineralization in Archaean terranes, from initial licence selection moving from the craton to district/camp scale, and criteria to aid target selection within an identified package of favourable stratigraphy.
6. Conclusions

Through our detailed analysis of Erayinia NW drillcore and extensive soil geochemistry over the region we have refined targets for VHMS exploration. The following conclusions can be drawn from our research.

1. Diamond drilling at Erayinia NW has identified widespread hydrothermal alteration and minor base metal mineralization across a strike length exceeding 3 km. A lower package of calc-alkaline mafic-ultramafic rocks, a mixed sequence of argillaceous sedimentary rocks interbedded with FI to FIII affinity dacitic rocks, and calc-alkaline mafic-ultramafic.

2. Hydrothermal alteration is most prevalent in a 50-75 m thick felsic sequence (quartz-sericite-pyrite) interbedded with black shales. Local zones of more intense chloritization are associated with Zn-Cu and massive pyrite mineralization in directly overlying mafic rocks in the southernmost drillholes.

3. New SHRIMP U–Pb zircon geochronology has constrained the age of the host stratigraphy to 2685 ± 5 Ma. Inherited zircons > 2.7 Ga in age are consistent with the presence of c. 2.77–2.72 Ga basement under the Gindalbie age volcanic rocks in the Eastern Goldfields.

4. Black shales and hydrothermally altered volcanic rocks contain high Eu/Eu* and anomalous concentrations of the following trace elements with increasing Zn abundance: Ag, As, Bi, Cd, Cu, Hg, In, Mo, Pb, Sb, Sn, Tl. Broad halos of Sb, TI, Eu/Eu* and normative corundum occur within this sequence.

5. Felsic rocks are characterized by higher abundances of white mica and less chlorite than surrounding strata. Increased quantities of Mg-rich chlorite, muscovitic (Al-rich) white mica, and Fe-carbonate ( siderite) occur proximal to Fe–Zn mineralization.

6. Together, the data from Erayinia NW is interpreted to reflect weak and distal hydrothermal alteration in the northern holes (particularly EC156D), with local zones of more intense chloritic alteration towards drillhole EC157D reflecting the movement of minor high temperature fluids away from the main site of hydrothermal up-flow and mineralization (as yet undiscovered). VHMS mineralization at Erayinia NW is most likely to be associated with a synvolcanic fault, in a volcanic vent proximal setting, associated with an FFII-affinity rhyolite dome. This may occur down-dip or along strike of the massive pyrite intersected in drillhole EC157D.

7. Soil metal concentrations at Erayinia vary significantly according to underlying regolith type (e.g. colluvium, alluvium, Playa Lake). Soil maps levelled by regolith type reveal multi-element bulls-eye geochemical anomalies (e.g. Zn, Pb, Cu, As, Bi, Cd, Mo, Mn, Ti, W) over the King deposit, King North occurrence, with new targets identified at Erayinia NW and elsewhere.

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Appendix A. Supplementary data

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