Review

A review of volcanic-hosted massive sulfide (VHMS) mineralization in the Archaean Yilgarn Craton, Western Australia: Tectonic, stratigraphic and geochemical associations

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A B S T R A C T

The Archaean Yilgarn Craton of Western Australia represents a world-class metallic province, host- ing considerable resources of Au, Ni-sulfides and iron ore. Despite close geological similarities with the volcanic-hosted massive sulfide (VHMS)-rich Superior Province of Canada, there is a strong disparity in the number of discovered VHMS deposits between the two areas. This paper brings together recently published U–Pb zircon geochronology and stratigraphic constraints from across the Yilgarn Craton, with a large number of existing whole rock geochemical datasets (881 samples from ~125 localities). Recognized VHMS occurrences are placed in a detailed tectonic and stratigraphic framework. Temporal and geochemical associations to mineralization are discussed. Areas of VHMS mineralization in the Yilgarn Craton are preferentially associated with areas of thinned, juvenile crust as revealed through regional (Nd, Pb) isotope variations. The characteristics identified here for prospective host sequences are: largely bimodal volcanic complexes, synvolcanic faults, a spatial and temporal association to HFSE-enriched syn-volcanic intrusions, and the following geochemical signatures of felsic rocks. VHMS-bearing felsic rocks in the Youanmi Terrane and Eastern Goldfields are characterized by low Zr/Y, La/YbCN and Th/Yb ratios, high Sc/TiO2, Sc/V, HFSE and HREE contents, and flat HREE profiles similar to those of Abitibi greenstone belt, Canada, and the Pilbara Craton of Western Australia. Chondrite-normalized REE profiles for felsic rocks overlying 2.82–2.80 Ga plume-related basalts and large igneous complexes of the Youanmi Terrane are flat. Other VHMS-bearing felsic rocks are characterized by slight LREE enrichment (La/SmCN < 3) and flattish HREE profiles. In the Youanmi Terrane four distinct periods of economic mineralization can be recognized: (i) >2.9 Ga (e.g. Golden Grove, Ravensthorpe), associated with early bimodal-mafic greenstone belts subjected to extension; (ii) c. 2.815 Ma (e.g. Austin, Just Desserts, Youanmi), following a major plume event and coeval with the emplacement of large igneous complexes across the northern Youanmi Terrane at shallow levels in the crust (Meeline and Boodanoo suites); (iii) 2760–2745 Ma (e.g. Hollandaire, Mt. Mulcahy) in areas of rift-related magmatism during the deposition of the Greensleevies Formation; (iv) c. 2725 Ma, in the Gum Creek greenstone belt associated with a second major plume event, broadly coeval with the deposition of high-level sills of the Yalgowra Suite. In the Eastern Goldfields Supergroup, VHMS mineralization formed between c. 2700 and 2680 Ma (e.g. Teutonic Bore camp, Anaconda, Nimbus, Erayinia). All episodes of VHMS mineralization in the Yilgarn show strong temporal and spatial associations to suites of HFSE-enriched granitic intrusions (e.g. Eelya suite, Mt. Kenneth suite, Kookynie supersuite).

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1. Introduction

The Archaean Yilgarn Craton of Western Australia represents a world-class metallogenic province, hosting considerable resources of Ni-sulfides, Au and iron ore (Barnes, 2006; Blewett et al., 2010a,b). Following the 1963 discovery of the giant Kidd Creek Cu–Zn deposit in Canada, the Archaean Yilgarn and Pilbara cratons of Western Australia were actively targeted for volcanic-hosted massive sulfide (VHMS) mineralization throughout most the 1960s and 1970s (McConachy et al., 2004). The main exploration technique was gossan searching (Butt, 2004) coupled with geophysics. One substantial find was made at Gossan Hill in 1971 (Goldene Grove camp; Ashley et al., 1988), and a smaller but higher grade find was made in 1976 at Teutonic Bore in the Eastern Goldfields Superterrane (Hallberg and Thompson, 1985) (Fig. 1; Table 1). By the early 1980s, the general lack of success and an increasing gold price saw a change in focus and VHMS mineralization effectively dropped off the exploration agenda in Western Australia for the next 25 years (Yeats, 2007). By 2004 only six significant base metal deposits had been brought into production out of all VHMS deposits hosted in Proterozoic and Archaean rocks of Western Australia – two of which were principally mined for Au (McConachy et al., 2004). Perhaps unsurprisingly, there has been much discussion about whether the Yilgarn Craton is intrinsically impoverished in VHMS mineralization or is simply underexplored (e.g. Witt et al., 1996; Ferguson, 1999; Brown et al., 2002; McConachy et al., 2004; Yeats, 2007; Vearncombe, 2010; Huston et al., 2014).

Historically there have been several major hindrances to VHMS exploration in the Yilgarn Craton, which is characterized by a paucity of outcrop, deep weathering and high strain (McConachy et al., 2004). Saline groundwater has tended to overwhelm electro-magnetic (EM) responses (Phillips, 2004), which combined with deep weathering, conductive overburden and intercalated black shale horizons in prospective sequences, has meant few deposits have been discovered using such techniques. Electromagnetics is the principle exploration tool for VHMS mineralization in Canada, and has only recently proven successful in the Yilgarn Craton (e.g. Jaguar deposit; Ellis, 2004). Although deep weathering in Australia increases the economics of some deposits (e.g. Nimbus: McConachy et al., 2004; Hollandaire: Hayman et al., submitted for publication), a poor understanding of regolith processes until recent decades (reviewed in Anand and Butt, 2010) has meant deep weathering often hindered exploration efforts. Recent developments in these fields and renewed exploration activity since the early 2000s has led to a number of new discoveries, including further successes at Golden Grove, Nimbus and Manindi, and new resources at Jaguar, Bentley, Austin, Just Desserts, Kundip and Hollandaire (Fig. 1; Table 1). VHMS mineralization has also been identified at sites across the Yilgarn Craton, such as at The Cup, Erayinia (King) and Copper Bore (Fig. 1).

This paper brings together recently published U–Pb zircon geochronology and stratigraphic constraints from across the Yilgarn Craton, with a large number of existing whole rock geochemical datasets (881 samples from ~125 localities). Recognized VHMS occurrences are placed in a detailed tectonic and stratigraphic framework. Temporal and geochemical associations to mineralization are discussed, including a temporal and spatial association to geochemically HFSE-enriched granitic intrusive rocks in both the Youanmi Terrane and Eastern Goldfields.

2. Regional geology

Through a combination of airborne magnetic surveys, detailed follow up mapping, greatly expanded geochronology and isotope terrane delineation, our understanding of the geology of the Yilgarn Craton has improved considerably in recent years (e.g. Champion and Sheraton, 1997; Cassidy et al., 2006; Champion and Cassidy, 2007; Czarnota et al., 2010; Ivanci et al., 2010; Pawley et al., 2012; Van Kranendonk et al., 2013; Mole et al., 2014). The Yilgarn Craton has historically been divided into a series of terranes based on distinct lithological associations, geochemistry and ages of volcanism (Gee et al., 1981; Myers, 1990; Cassidy et al., 2006). The western half of the Yilgarn Craton comprises the Narryer, South West and Youanmi terranes (Fig. 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; Fig. 1). Terranes are further divided into domains, all of which are bounded by an interconnected system of faults.

Competing models for the formation of the Yilgarn Craton vary from anca subduction, arc and/or plume magnatism, and the accretion of allochthonous terranes (discussed in Czarnota et al., 2010; Barnes et al., 2012; Van Kranendonk et al., 2013). Debate primarily concerns whether subduction is required to explain the
Table 1
VHMS resources in the Youanmi Terrane and Eastern Goldfields Superterrane, Yilgarn Craton.

<table>
<thead>
<tr>
<th>Terrane</th>
<th>Domain</th>
<th>Age (Ma)</th>
<th>Deposit</th>
<th>Year of discovery</th>
<th>Mt Cu (%)</th>
<th>Mt Zn (%)</th>
<th>Mt Pb (%)</th>
<th>Mt Ag (g/t)</th>
<th>Mt Au (g/t)</th>
<th>Resource reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Youanmi</td>
<td>Murchison</td>
<td>ca. 2960–2930</td>
<td>Gossan Hill</td>
<td>1971</td>
<td>15.9</td>
<td>2.6</td>
<td>1.5</td>
<td>0.2</td>
<td>21</td>
<td>Gawlinski (2004); McConachy et al. (2004); MMG (2011); *pre-mining reserves</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Scuddles</td>
<td>1979</td>
<td>10.5*</td>
<td>1.2</td>
<td>11.7</td>
<td>0.8</td>
<td>89</td>
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<td></td>
<td></td>
<td></td>
<td>Amity</td>
<td>1999</td>
<td>1.91</td>
<td>15.1</td>
<td>1.4</td>
<td>93</td>
<td>2.0</td>
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<td></td>
<td></td>
<td></td>
<td>Hougoumont</td>
<td>1999</td>
<td>0.56</td>
<td>21.5</td>
<td>7.5</td>
<td>305</td>
<td>6.2</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Catalpa</td>
<td>1999</td>
<td>0.63</td>
<td>15.5</td>
<td>1.6</td>
<td>185</td>
<td>2.7</td>
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<td></td>
<td></td>
<td></td>
<td>Ethel</td>
<td>2000</td>
<td>0.45</td>
<td>20.7</td>
<td>2.5</td>
<td>5.8</td>
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<td></td>
<td></td>
<td></td>
<td>Xantho</td>
<td>2003</td>
<td>0.4</td>
<td>11.9</td>
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<td></td>
<td></td>
<td></td>
<td>Cambewarra</td>
<td>2003</td>
<td>0.14</td>
<td>13.3</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>Gossan Valley/Felix</td>
<td>1971–1972/1979</td>
<td>1.5</td>
<td>7.9</td>
<td>10</td>
<td>0.9</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.3</td>
<td>2.3</td>
<td>14</td>
<td>0.3</td>
<td></td>
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<td></td>
<td></td>
<td>ca. 2930</td>
<td>Mt Gibson</td>
<td>1975</td>
<td>25.9</td>
<td></td>
<td></td>
<td></td>
<td>1.94</td>
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<td></td>
<td></td>
<td>ca. 2746</td>
<td>Hollandaire</td>
<td>2011</td>
<td>2.8</td>
<td>1.6</td>
<td></td>
<td>5</td>
<td>0.4</td>
<td>McConachy et al. (2004)</td>
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<tr>
<td></td>
<td></td>
<td>ca. 2718</td>
<td>Austin (Quinns)</td>
<td>2008</td>
<td>1.48</td>
<td>1.02</td>
<td>1.39</td>
<td>3.31</td>
<td>0.24</td>
<td>Inferred resource. Silver Lake Resources (2013a)</td>
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<td></td>
<td></td>
<td>ca. 2814</td>
<td>Manindi (Freddie Well)</td>
<td>1972</td>
<td>1.35</td>
<td>0.25</td>
<td>6.04</td>
<td>3.4</td>
<td>0.25</td>
<td>Maiden resource. Silver Swan (2012)</td>
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<tr>
<td></td>
<td></td>
<td>ca. 28157</td>
<td>Mt. Mulcahy</td>
<td>1972</td>
<td>0.25*</td>
<td>3.77</td>
<td>2.75</td>
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<tr>
<td>Youanmi</td>
<td>Southern Cross</td>
<td>ca. 2813</td>
<td>Just Desserts</td>
<td>2007–2008?</td>
<td>1.07</td>
<td>1.82</td>
<td></td>
<td></td>
<td>0.8</td>
<td>JORC resource. Empire Resources (2012)</td>
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<tr>
<td></td>
<td></td>
<td>ca. 2950</td>
<td>Kundip</td>
<td>–</td>
<td>8.94</td>
<td>0.3</td>
<td>2.3</td>
<td>2.7</td>
<td>Silver Lake Resources (2013b)</td>
<td></td>
</tr>
<tr>
<td>Kurnalpi</td>
<td>Gindalbie</td>
<td>ca. 2690</td>
<td>Teutonic Bore</td>
<td>1976</td>
<td>1.68*</td>
<td>3.5</td>
<td>10.7</td>
<td>140</td>
<td>*Production to end-1984 (Ellis, 2004); **Pre-mining reserve (Jabriu Metals 2006); **Pre-mining resource (indicated and inferred) (Jabriu Metals, 2010)</td>
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<td></td>
<td></td>
<td></td>
<td>Jaguar</td>
<td>2002</td>
<td>1.60**</td>
<td>3.1</td>
<td>11.3</td>
<td>0.7</td>
<td>115</td>
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<td></td>
<td></td>
<td></td>
<td>Bentley</td>
<td>2008</td>
<td>3.05***</td>
<td>2.0</td>
<td>9.8</td>
<td>0.6</td>
<td>139</td>
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<td></td>
<td></td>
<td></td>
<td>Anacoda</td>
<td>Historic</td>
<td></td>
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<td>Historic Cu production (4595t)</td>
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<tr>
<td>Murrin</td>
<td>ca. 2700</td>
<td>Anacoda</td>
<td>Historic</td>
<td>Historic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Marston (1979)</td>
<td></td>
</tr>
<tr>
<td>Kalgoorlie</td>
<td>Boorara</td>
<td>ca. 27007</td>
<td>Nimbus</td>
<td>1993</td>
<td>4.88</td>
<td>1.33</td>
<td>79</td>
<td>0.29</td>
<td>Resource as of 25th July 2013. (MacPhersons, 2014)</td>
<td></td>
</tr>
</tbody>
</table>

Adapted from McConachy et al. (2004).
evolution of the EGS and which of the various terranes and domains have a common history. While a number of workers favour both plume and subduction processes (Czarnota et al., 2010; Huston et al., 2014), others highlight the problem of scale as plume magnetism is expected to overwhelm subduction (Barnes et al., 2012; Van Kranendonk et al., 2013; Barnes and Van Kranendonk, 2014). Evidence for a common history between the Youanmi Terrane and EGS, includes: (i) contemporaneous plume magnetism across the EGS and Youanmi Terrane from at least c. 2.82 Ga (Ivanic et al., 2010; Barnes et al., 2012); (ii) contemporaneous and voluminous granitic magnetism across the whole craton prior to the timing of inferred accretion (Czarnota et al., 2010); (iv) simultaneous inferred ‘subduction-related’ magnetism across the whole of the craton inconsistent with the geometry of modern arc systems (Van Kranendonk et al., 2013); and (v) stratigraphic and isotopic similarities between the Kalgoorlie and Youanmi terranes, and Youanmi and Burtville terranes (Pawley et al., 2012; Mole et al., 2014). The issue remains highly contentious and the two models will be discussed further in Section 2.3 (Eastern Goldfields Superterrane).

2.1. Narryer and South West terranes

The Narryer and South West terranes of the western Yilgarn Craton are dominated by granite and granitic gneiss with minor supracrustal greenstone inliers (Fig. 1). The c. 3.7 Ga Manfred Complex (a dismembered layered igneous complex) and Meeberrie Gneiss (a sequence of felsic intrusive rocks) represent the oldest sequences of the Narryer Terrane (Wyche et al., 2013). Both were intruded by felsic magmas (c. 3.3 Ga; e.g. Dugel and Eurada gneisses) and deformed and metamorphosed between amphibolite and granulite facies prior to the deposition of supracrustal rocks (e.g. Jack Hills greenstone belt) (Wyche et al., 2013). Early Archaean gneisses of the Narryer Terrane may represent an allochthon thrust over 3.0–2.9 Ga granitic crust of the Youanmi Terrane (Wyche et al., 2013).

The South West Terrane comprises strongly deformed, high-grade granite-gneiss, metasedimentary and metagneous rocks intruded by 2750–2620 Ma granites and pegmatites (Mole et al., 2012). Supracrustal successions range in age from 3200 to 3010 Ma in the Chittering, Jimperding and Balingup(?) metamorphic belts.
and the Wongan Hills greenstone belt, to 2715–2675 Ma in the Sadleback and Moranup greenstone belts (e.g. Pidgeon and Wilde, 1990; Mole et al., 2012; Fig. 1).

2.2. Youanmi Terrane

It is now clear through regional mapping, SHRIMP and isotope data (e.g. Van Kranendonk et al., 2013) that the Murchison Domain and northern part of the Southern Cross Domain (Fig. 1) largely share a common history and were not brought together by an accretionary event (Ivanic et al., 2010; Wyche et al., 2013). Isotope studies reveal a long process of crustal formation and reworking in the Youanmi Terrane (Champion and Cassidy, 2007; Ivanic et al., 2012; Wyche et al., 2012; Mole et al., 2014). Detrital zircons in quartzites and xenocrystic zircons from intrusive and extrusive rocks date back to >4.0 Ga (Nelson, 1997; Wyche, 2007), Van Kranendonk et al. (2013) recently presented a revised stratigraphy for the long-lived, autochthonous Murchison Domain (Fig. 2), which is likely comparable to the northern part of the Southern Cross Domain. Early supracrustal sequences in the Murchison which formed prior to 2.9 Ga are locally preserved in the Yalgoo-Singleton (c. 2.96–2.93 Ga: Wang, 1998), Weld Range (c. 2.97 Ga: Wingate et al., 2008), Tallering (c. 2.94 Ga) and Twin Peaks (c. 3.0 Ga: Pidgeon and Wilde, 1990) greenstone belts. All of these greenstone belts contain VHMS mineralization. In the Southern Cross Domain, supracrustal sequences of similar age (i.e. >2.9 Ga) occur in the Ravenstorpe (c. 3.0–2.95 Ga: Witt, 1999), Koolyanobbing (c. 3.0 Ga: Angerer et al., 2013), Marda-Diemals (c. 3.0 Ga: Chen et al., 2003), Forrestania (c. 2.9 Ga: Perrin et al., 1996), Southern Cross (c. 2.93–2.91 Ga: Mueller and McNaughton, 2000) and Lake Johnston (c. 2.92–2.78 Ga: Romano et al., 2013) greenstone belts.

Following an extended depositional hiatus across the Youanmi Terrane (<110 Myr), the unconformably overlying 2825–2805 Ma Norie Group was deposited (Van Kranendonk et al., 2013; Fig. 2). Exposed predominantly across the northern part of the Murchison Domain, the Norie Group records a major mantle melting event at c. 2.82 Ga which resulted in the emplacement of large mafic–ultramafic layered intrusions (Ivanic et al., 2010) and the eruption of the Murruoli Basalt Formation (Watkins and Hickman, 1990; Van Kranendonk et al., 2013). This significant mantle melting event, possibly plume-related (Ivanic et al., 2010, 2012; Nebel et al., 2013), may have resulted in the partial breakup of the proto-Yilgarn Craton, with E-W extension marked by younger Nd isotope model ages (Fig. 3; Czarnota et al., 2010; Huston et al., 2014). These areas of thinned, juvenile crust (e.g. Cue Zone; Fig. 3) have been linked to subsequent episodes of VHMS mineralization across the Yilgarn Craton (Huston et al., 2005, 2014). The Murruoli Basalt Formation comprises a c. 4 km thick sequence of interbedded Ti-rich, Al-depleted komatiites and komatitic volcaniclastic rocks overlain by tholeiitic basalts (Barley et al., 2000). Conformably overlying rocks of the 500 m thick Yalogoinda Formation are dominated by felsic volcanic and volcaniclastic sedimentary rocks and interbedded units of fanglomerate and/or BIF (Van Kranendonk et al., 2013; Fig. 2). Felsic volcanic rocks coeval with the Yalogoinda Formation also overlie the large 2.82 Ga layered intrusions (e.g. Windimurra and Narrdegee igneous complexes) as the Kanite Murdiana Volcanics Member. Both the Yalogoinda Formation and Kanite Murdiana Volcanics Member host significant VHMS mineralization around Quinns, Narrdegee, Windimurra and Youanmi (Fig. 4).

The 2800–2730 Ma Polelle Group (?dis) conformably overlies the Norie Group and consists of the following formations (Fig. 2): (i) Coodardy – characterized by a thin (100 m thick) unit of basal quartzite and BIF; (ii) Meekatharra – comprising a 2.5 km thick sequence of tholeiitic basalt, komatiitic basalt, komatiite and thin interflow 2800–2760 Ma felsic volcaniclastic sedimentary rocks; (iii) Greensleeves – dominated by a ≤5 km thick, 2760–2740 Ma, VHMS-bearing andesitic to rhyolitic volcanic and volcaniclastic rocks; and (iv) Wilgie Mia – characterized by interbedded BIF, shale and felsic volcaniclastic rocks (Van Kranendonk et al., 2013). Subduction affinity magmatism during the Greensleeves Formation, coupled with the postulated existence of boninites, may be related to convergence between the Narryer and Youanmi terranes (Wyman and Kerrich, 2012). A second (less-significant) unconformity separates the Polelle Group from the overlying 2735–2700 Ma Glen Group (Fig. 2), which includes the: (i) Ryansville Formation – dominated by clastic sedimentary rocks; and (ii) Wattagee Formation – characterized by komatitic basalt and subordinate rhyolite. The deposition of the Wattagee Formation was coeval with the emplacement of widespread, thick and differentiated sills of the Yalgowra Suite (Figs. 2 and 4), predominantly hosted in the older Greensleeves Formation (Ivanic et al., 2010; Wyche et al., 2013) and komatitic volcanism in the EGS (Section 2.3; Fig. 5).

In the northern part of the Southern Cross Domain, similar greenstone sequences have been recognized to those of the Murchison Domain. In the Marda-Diemals greenstone belt a lower VHMS-bearing greenstone sequence proposed to be c. 3.0 Ga in age (Chen et al., 2003) is unconformably overlain by the calc-alkaline (and possibly subduction related: Morris and Kirkland, 2014) c. 2730 Ma Marda Complex and the clastic Diemals Formation. Recent U–Pb zircon geochronology on an intrusive gabbro (c. 2.8 Ga: Wingate et al., 2011b) from the lower greenstone sequence suggest it may be equivalent to mafic rocks which intrude the Norie Group at this time (Fig. 2), implying the Murchison and northern part of the Southern Cross Domains shared a common history prior to 2.8 Ga (Riganti et al., 2010). Similar assemblages to the lower greenstone sequence also occur in the Booyool Range greenstone belt of unknown age (Wyche et al., 2013). Further north in the Southern Cross Domain, the c. 2722 Ma Gum Creek greenstone belt (Bodorkos et al., 2006) is characterized by VHMS-bearing felsic volcanic/volcanoclastic rocks, clastic sedimentary rocks and abundant graphitic shale (e.g. The Cup, Bevan: Fig. 1). Granitic rocks constrained to c. 2800 Ma (Wingate and Bodorkos, 2007b) intrude the northern end of the Gum Creek greenstone belt, indicating an older age for part of the local stratigraphy.

2.3. Eastern Goldfields Superterrane (EGS)

In the Eastern Goldfields Superterrane at least four distinct periods of volcanism are preserved: (i) at c. 2940 Ma in the Kalgoorlie and Burtville terranes; (ii) a fragmentary record from c. 2810 Ma in the northern Kalgoorlie, Kurnalpi and Burtville terranes (Wiluna, Laverton and Duketon domains respectively); (iii) at c. 2760 Ma in the Burtville Terrane (Merolia Domain); and (iv) a more consistent record from c. 2715 Ma in all terranes (Fig. 4; Czarnota et al., 2010). Although local stratigraphy has been established for a number of greenstone belts of the EGS, a detailed regional stratigraphy has only been described for the southern part of the Kalgoorlie Terrane (Fig. 5). This consists of a lower 2710–2692 Ma mafic–ultramafic succession (Beresford et al., 2005; ‘Kambalda Sequence’: Fig. 5) succeeded by the 2690–2660 Ma ‘Kalgoorlie Sequence’ (Krapeed and Hand, 2008). The latter is characterized by a >3 km thick package of volcaniclastic rocks, felsic volcanic rocks, mafic intrusive complexes with minor mafic volcanic rocks (Squire et al., 2010).

The mafic–ultramafic succession is related to a major plume event in the Yilgarn Craton at 2.72 Ga, broadly contemporaneous with komatiitic magmatism in the Wattagee Formation of the Youanmi Terrane and the emplacement of the Yalgowra Suite (Fig. 2). The occurrence of geochemically similar komatiites and basalts at the same relative stratigraphic position across the Kalgoorlie and Kurnalpi terranes of the EGS between 2705 and 2690 Ma suggest the eastern Yilgarn Craton was assembled by 2705 Ma.
Plume-related komatiitic cumulate bodies of the Kalgoorlie Terrane host world-class Ni resources such as Mt. Keith and Black Swan (Barnes, 2006; Barnes and Fiorentini, 2012). These cumulate bodies are interpreted as the products of high-flux komatiite volcanism focused along the eastern margin of the Youanmi Terrane. Thin, sparsely distributed komatites of the Kurnalpi Terrane most likely represent thin flows or ponded lava lakes distal to the main source of volcanism (Barnes et al., 2012).

Between 2692 and 2680 Ma volcanic centres in the western Kurnalpi Terrane (Gindalbie Domain: Fig. 1) are associated with largely bimodal (basalt-rhyolite) volcanic and associated sedimentary rocks, although some contain significant volumes of andesites. These rocks have been attributed by some workers as forming in arc-rift environments (see following) and are broadly contemporaneous with the early Black Flag Group of the Kalgoorlie Terrane (Fig. 5). VHMS mineralization in the central EGS is closely associated with HFSE-enriched felsic volcanic rocks, with significant resources occurring in close proximity to geochemically similar and coeval large granitic suites (Fig. 6; see Section 6.2). Late doming and extension associated with the emplacement of a widespread high-Ca tonalite-trondjhemite-granodiorite (TTG) suite produced the late clastic basins of the Yilgarn Craton (Wyche et al., 2013; Fig. 5).

Fig. 2. Stratigraphic scheme for the Murchison Domain within the Youanmi Terrane, divided into three main columns for supracrustal rocks, granitic rocks and ultramafic–mafic intrusive rocks (Van Kranendonk et al., 2013). Granitic suites which display HFSE-enriched geochemical characteristics are highlighted. Areas associated with the four main periods of VHMS mineralization in the Youanmi Terrane (as indicated by grey bars) include: 1 – Golden Grove, Raventhorpe, Twin Peaks, Tailerine, Weld Range; 2 – Copper Bore, Just Desserts, Quinns (Austin), Pincher Well, Narndee, Manindi, Chunderloo, Windimurra, Copper Hills, Barrambie; 3 – Hollandaire, Mt. Mulcahy, Emily Well, Chesterfield/Jilliewarra, Abbotts; 4 – Gum Creek greenstone belt (The Cup, Bevan, Eds Bore); Watatagee Well (?), Marda Complex (?). (A)–(I) represent U–Pb zircon ages for HFSE-enriched granitic rocks: (A) Mount Gibson monzogranite (Yeats et al., 1996); (B) Courlbaroo tonalite (AMIRA P482: Fletcher and McNaughton, 2002); (C) Peter Well biotite granite (Wingate et al., 2010b); (D) Elyya granitoid (Wang ANU unpublished cited by Fletcher and McNaughton, 2002); (E) Peter Well monzogranite (Wang, 1998); (F) Peter Well granodiorite (Wang, 1998); (G) Keygo granophyric granodiorite (Fletcher and McNaughton, 2002); (H) Butcher Bird granophyre (Nelson, 2001a); (I) Montague monzogranite (Wang et al., 1998); (J) Dampierwah granite (Wiedenbeck and Watkins, 1993); (K) Coolamen hornblende-biotite granite (Fletcher and McNaughton, 2002); (L)–(R) represent U–Pb geochronology ages for ultramafic–mafic intrusive rocks: (L) Gabaninha gabbro (Wang, 1998); (M) Narndee gabbro (Ivanic et al., 2010); (N) Murrouli dolerite (Wang, 1998); (O) Fleece Pool gabbro (Ivanic et al., 2010); (P) Kathleen Valley gabbro (Liu et al., 2002); (Q) Dalgaranga dolerite (Pidgeon and Hallberg, 2000); (R) Wuladah gabbro (Ivanic et al., 2010).
high heat flow. Regardless of whether subduction was involved, Nd isotope data clearly indicates VHMS mineralization occurred along the margins of rift-zone (either back-arc or intra-cratonic) characterized by juvenile Pb isotope signatures (low $\mu$: <8.3) and younger Nd$_{DM}$ ages (see Fig. 3; Huston et al., 2014).

Recent work by Pawley et al. (2012) has detailed the stratigraphy of the Burtville and Yamarna terranes of the easternmost Yilgarn Craton (Supplementary Fig. 1). Four main episodes of crustal growth were recognized at 2970–2910 Ma, 2815–2800 Ma, 2775–2735 Ma and 2715–2630 Ma. Whereas the Burtville Terrane has affinities with the Youanmi Terrane, the Yamarna Terrane has affinities with the Kalgoorlie Terrane (Fig. 5; Supplementary Figure). Pawley et al. (2012) suggested extension and thinning at c. 2720 Ma led to the separation of the Burtville and Youanmi terranes (also discussed in Mole et al., 2014), although this is again controversial. Xenocrystic zircons (>2.72 Ga) and >3000 Ma Nd model ages in granites and volcanics also suggest that older crust remains beneath the juvenile terranes of the EGS (Mole et al., 2014).

### 3. What is petrochemically prospective?

In the last 25 years, major advances have been made in petrochemical (Lesher et al., 1986; Lentz, 1998; Wyman, 2000; Piercey et al., 2001; Hart et al., 2004; Piercey, 2011) and lithochemical VHMS exploration (e.g. element mobility, hyperspectral logging and mapping). This is partly due to the routine application and increasingly low costs of multi-element ICP-MS geochemistry, which has allowed exploration companies to plan drilling campaigns based on the identification of VHMS favourable host sequences and hydrothermal assemblages. VHMS deposits form in volcanic successions due to focused heat flow associated with hydrothermal convection, which is the result of tectonic extension, mantle depressurization and the formation of high temperature melts (Galley, 1993, 2003; Franklin et al., 2005; Galley et al., 2007).

Ultimately, petrochemical assemblages of mafic and felsic rocks indicative of an extensional tectonic setting and high temperature heat flow at shallow crustal levels are desired (Lesher et al., 1986; Hart et al., 2004; Piercey, 2011).
Lesher et al. (1986) first proposed a threefold division of VHMS-fertile versus barren felsic rocks from the Superior Province of Canada (FI–FIIIb type). This scheme was subsequently applied to Proterozoic and Phanerozoic deposits worldwide, and modified to include FIV affinity felsic rocks common to post-Archaean primitive arcs (Barrie et al., 1993; Lentz, 1998; Piercey et al., 2001; Hart et al., 2004). FI affinity felsic rocks are typically calc-alkaline (i.e. high Zr/Y, La/Yb, Th/Yb), with relatively high high field strength element (HFSE) concentrations and strongly light-REE (LREE) enriched chondrite-normalized REE profiles relative to the heavy-REE (HREE). This petrochemically unfavourable suite is indicative of deep melting and therefore reduced crustal heat flux. Geochemical characteristics are due to the retention of Sc, Y and the HREE by garnet (and to a lesser extent amphibole) in the source region. The FII suite represents an intermediate stage between FI and FIII affinity felsic rocks. FIII affinity felsic rocks are characterized by low Zr/Y and La/Yb, flat and tholeiitic chondrite-normalized REE patterns, and elevated HFSE contents (especially Y, Zr > 200 ppm) (Piercey, 2011). In Archaean environments VHMS deposits are preferentially associated with FIII (and to a lesser extent FII) affinity rhyolites. These rocks are interpreted to have formed within rift sequences from high-temperature melts (T>900 °C) at shallow to mid-crustal depths during extension (Piercey, 2011). Rhyolites associated with continental rifts or continental back-arc rifts often display extreme HFSE concentrations and higher REE contents (Leat et al., 1986; McConnell et al., 1991; Dusel-Bacon et al., 2012). The FIV suite of Hart et al. (2004) is of little interest here as these rocks are predominantly restricted to post-Archaean primitive-arc sequences (Piercey, 2011).

Although the above scheme is broadly applicable to most VHMS-hosting felsic rocks worldwide, there are a number of important exceptions: (i) post-Archaean deposits associated with continental crust; and (ii) Au-rich VHMS deposits. It is well established that rhyolites associated with the post-Archaean VHMS-rich Finlayson Lake, Que River, Kuroko and Mount Windsor regions can display elevated Zr/Y and La/YbCN ratios and FI affinities (Ohmoto and Skinner, 1983; Piercey et al., 2001, 2008). As noted by Piercey et al. (2008), although such rocks can display ‘petrochemically unfavourable’ high Zr/Y and La/YbCN ratios, they often retain the common HFSE and REE enrichment typical of VHMS-hosting felsic
rocks worldwide. As the Lesher et al. (1986) classification scheme was initially conceived for use in Archaean environments, which are dominated by basaltic substrate, it has its limitations in Proterozoic and Phanerozoic terranes. In these instances, high La/YbCN and Zr/Y ratios not only reflect the depth of melting but also the efficiency of melting HFSE and REE enriched accessory phases of continental crust (discussed in Piercey et al., 2008).

In their recent review of Au-rich VHMS deposits, Mercier-Langevin et al. (2011) noted that most deposits occur at specific stratigraphic positions and volcanic settings, which differ from the Cu–Zn deposits in these districts. It has been suggested that the Au-rich LaRonde deposit formed closer to the subduction zone, associated with the rifting of thicker crust than the typical Cu–Zn Noranda-type VHMS deposits (Mercier-Langevin et al., 2007). Again, partial melting of (or contamination by) continental crust during the genesis of felsic rocks will lead to high La/Yb and Zr/Y ratios. The hybrid characteristics of Au-rich VHMS deposits towards epithermal-style mineralization are consistent with their formation at shallower water depths, further from the back-arc spreading centre (Mercier-Langevin et al., 2011). No Au-rich VHMS deposits have been identified in the Yilgarn Craton, although the Ag-rich Nimbus deposit (Fig. 1) has many characteristics of a shallow water and low temperature VHMS deposit.
4. Geochemistry: methods

To investigate the geochemistry of felsic rocks across the Yilgarn Craton whole rock geochemical data was compiled from a number of datasets (listed in the Appendix). This is complemented by new Geological Survey of Western Australia (GSWA) geochemistry from the EGS (Anxiety Bore, Kookynie, Teutonic Bore and Rocky Dam) and Gum Creek greenstone belt (Montague Ultramafic). All geochemical analyses were divided into lithological groupings based on original sample descriptions. Those classified as ultramafic, mafic, granite-gneiss, banded iron formation and sedimentary rocks were removed. Intermediate and felsic rocks were retained due to their occurrence at a number of VHMS deposits (e.g. Golden Grove, Teutonic Bore camp, Mt. Gibson, Hollandia). Mafic associations to VHMS mineralization will be discussed elsewhere. The database presented here (Supplementary Information) includes 881 samples from intermediate and felsic rocks from ~125 localities across the Yilgarn Craton (Fig. 7). As the datasets included herein were produced using various techniques, over several decades, from different laboratories, careful consideration was given to detection limits. Historically, most trace element data would have been obtained by XRF analysis, which has significantly poorer detection limits than modern ICP-MS analysis (e.g. REE, Th, Nb, Ta, Hf). It was clear that for a number of the published datasets, results below detection had been set to specific values (e.g. 0.5 x detection limits). To maintain a high degree of quality in the retained database results below 1.5 x XRF trace element detection limits were removed. Cut off values predominantly affected ultramafic and mafic rocks which are not of interest here. The only exception for the above rule was for the REE, which were retained if the analysis included the HREE and was obtained by ICP-MS in recent years; or displayed relatively smooth chondrite-normalized profiles. Ta and Hf data were also retained, although no ratios were calculated using these elements. Major element data were recalculated to 100% excluding LOI, S, CO₂ and H₂O°. Trace elements were recalculated using the same corrections to maintain element ratios. Iron is reported as Fe₂O₃T calculated from FeO and Fe₂O₃ values after the method of Grunsky (2013).

Following the subdivision of samples into lithology groupings based on rock descriptions and the removal of questionable low concentration data, samples were geochemically classified using a number of standard published diagrams. This was primarily to check if samples had been correctly described in the first instance. Due to the extensive metamorphism and hydrothermal alteration...
across the Yilgarn Craton, elements easily mobilized by hydrothermal fluids should be avoided for classification purposes (e.g. SiO$_2$, K$_2$O, CaO, Na$_2$O, MgO, Sr; 8a: MacLean, 1990). Silification and sericitisation is a common feature of hydrothermally altered volcanic rocks and consequently the Total Alkali–Silica diagram is of limited use (e.g. Fig. 8a), showing considerable scatter for intermediate and felsic rocks. Large mass gains of SiO$_2$ are not always apparent in analytical data due to the effects of closure. Immobile element classifications using bivariate plots that do not use ratios (e.g. Th-Co diagram of Hastie et al., 2007) are also not suitable for hydrothermally altered rocks subjected to significant mass change (MacLean, 1990). A more appropriate method for classifying altered volcanic rocks is using immobile element ratios, such as Zr/TiO$_2$ and Nb/Y (Pearce, 1996). From comparison between rock descriptions and the Pearce (1996) diagram, there is some scatter for mafic (not shown) and felsic rocks towards intermediate Zr/TiO$_2$ ratios (Fig. 8b). This may be due a combination of five possible causes: (i) xenocrystic zircons may lead to uncharacteristically high Zr/TiO$_2$ ratios; (ii) the samples may have not been correctly named in the first instance; (iii) the data fall within the ‘noise’/error of the classification diagram; (iv) the HFSE were not strictly immobile; and (v) basalts classify as intermediate compositions because their mantle sources were modified by subduction melts with high Zr/TiO$_2$ ratios (see Pearce, 1996). However, considering the original error ellipses of Pearce (1996) the majority of the felsic and intermediate data plot in the appropriate fields (Fig. 8b and c).

After samples were classified into rock types their magmatic affinity was investigated using the schemes of MacLean and Barrett (1993); modified by Barrett and MacLean (1994). Tholeiitic volcanic rocks are distinguished from calc–alkaline affinity volcanic rocks using Zr/Y, Th/Yb and La/Yb ratios. Traditional approaches using the AMF diagram (Irvine and Baragar, 1971) are not appropriate due to element mobility. Although the original MacLean and Barrett (1993) scheme was recently refined (Ross and Bédard, 2009), we have retained the original values herein. The Ross and Bédard (2009) classification scheme was constructed using minimal felsic rocks (<4% were phylitic) and consequently offers little discrimination for different felsic suites (FI–FIV) of interest for VHMS deposits. The term transitional is used herein to refer to geochemical characteristics between tholeiitic and calc–alkaline magmas, not subalkaline and alkaline magmas. Chondrite-normalized La/Sm, Dy/Yb and La/Yb ratios were calculated using values from McDonough and Sun (1995). For samples which lacked grid-coordinates (Whitford and Ashley, 1992; Yeats and Groves, 1998; Sharpe and Gemmell, 2001) prospect/deposit coordinates from the GSWA mineral occurrence database MINDEXE were used.

5. Geochemistry of felsic rocks in the Yilgarn craton

Few studies have been published detailing the style and setting of individual VHMS deposits of the Yilgarn Craton (reviewed in Barley, 1992; Large, 1992; Ferguson, 1999; McConachy et al., 2004; Yeats, 2007). Geochemical studies on the host-sequences of deposits are restricted to those at Gossan Hill (Sharpe and Gemmell, 2001), Scuddles (Whitford and Ashley, 1992); Mount Gibson (Yeats and Groves, 1998), Teutonic Bore (Hallberg and Thompson, 1985), Jaguar (Belford, 2010; Belford et al., in preparation), Hollandia (Hayman et al., submitted for publication), Yummiery (i.e. Just Desserts: Hassan, 2014) and Weld Range (Guillaume, 2013). Although high-quality geochemical data is available for felsic rocks associated with these areas, the sample distribution elsewhere in the Yilgarn Craton is patchy (Fig. 7). No data were found for several recent discoveries (e.g. Bentley, The Cup), and the Twin Peaks and Tailing greenstone belts. The petrogenesis of intermediate and felsic rocks from the Youanmi Terrane and EGS are discussed in detail by Van Kranendonk et al. (2013); also Wyman and Kerrich (2012), and Barnes and Van Kranendonk (2014) respectively, and is beyond the scope of this paper.

5.1. Areas associated with VHMS mineralization

The geochemistry of felsic and intermediate volcanic/volcaniclastic rocks of the Yilgarn Craton is presented in Figs. 9–13. Through comparisons to the VHMS-rich Abitibi greenstone belt of Canada (Lesher et al., 1986; Barrie et al., 1993) it is clear felsic rocks of the Yilgarn Craton display a similar, broad range of geochemical characteristics, ranging from unprospective (FI affinity) to highly-prospective (FIllB affinity) (Figs. 9 and 10; MacLean and Hoy, 1991; Mercier-Langevin et al., 2007; Gaboury and Pearson, 2008). VHMS-bearing felsic rocks in the Yilgarn Craton (e.g. Golden Grove, Jaguar, Hollandia, Dalgaranga, Youanmi, Gum Creek) are similar to those of the VHMS-rich camps of the Abitibi greenstone belt and the Pilbara Craton of Western Australia (Figs. 9 and 10; discussed below).

VHMS-associated (and prospective) felsic rocks are characterized by:

- high SiO$_2$ in unaltered rocks,
- tholeiitic to transitional Zr/Y and La/Yb values and FI to dominantly FIll characteristics (Figs. 9, 10 and 13),
- flattish REE profiles (La/Sm$_{CN}$ < 3; Dy/Yb$_{CN}$ ratios ~1; Figs. 11 and 12),
- high HFSE (Y, Nb, Zr, Sc) concentrations (Fig. 10),
- high Sc/TiO$_2$ and Sc/V (Fig. 9),
- low V and Th/Yb (Th/Yb < 2 and Th > 5 ppm; Fig. 13).

The high HFSE and HREE concentrations allow VHMS-bearing/prospective units to be distinguished from VHMS-barren/unprospective felsic rocks using ratios (e.g. Zr/Y, Sc/TiO$_2$) and absolute concentrations (e.g. A-type affinities). Felsic rocks associated with VHMS mineralization and those which display prospective geochemical characteristics are restricted to four periods in the Youanmi Terrane: (i) >2.9 Ga greenstone belts (e.g. Golden Grove, Weld Range, Ravensthorpe); (ii) c. 2815 Ma Yaloginda Formation and Kantine Murdana Volcanics Member (e.g. Quinnss/Austin, Narndee, Windimurra); (iii) c. 2750 Ma Greensleeves Formation (e.g. Hollandia, Chesterfield, Dalgaranga); and (iv) c. 2725 Ma Gum Creek greenstone belt (Figs. 2 and 10). Felsic rocks which lack VHMS mineralization and display unprospective geochemical signatures (i.e. steep, TTG-like REE profiles) have also been recognized from each of these periods except those which formed at c. 2815 Ma (e.g. Figs. 10 and 11). These rocks are equivalent to the TTG and TTG–high Gd/Yb groups of Barnes and Van Kranendonk (2014), and are considered unprospective for mineralization.

Chondrite-normalized REE profiles for VHMS-associated c. 2815 Ma felsic rocks of the Youanmi Terrane (i.e. Yaloginda Formation and Kantine Murdana Volcanics Member) are flat (Fig. 11d). Other VHMS-bearing units are characterized by slight LREE enrichment (La/Sm$_{CN}$ < 3) and flat HREE profiles (Dy/Yb$_{CN}$ ratios ~ 1 or less) (e.g. Figs. 11 and 12). HREE concentrations (e.g. Yb$_{CN}$) are higher in VHMS-associated felsic rocks than unprospective units (Figs. 9 and 10). In some instances, Dy/Yb$_{CN}$ values < 1 and slight LREE-enrichment (La/Sm$_{CN}$ < 3) produce weakly U-shaped chondrite-normalized REE profiles (e.g. Golden Grove Formation: Fig. 11a). For the REE, the best discrimination is provided by Dy/Yb$_{CN}$ ratios, as HREE profiles are typically flat and Yb concentrations are often higher in VHMS associated felsic rocks. La/Yb$_{CN}$ ratios of felsic rocks associated with VHMS mineralization are also
lower than unprospective units (due to LREE-enrichment over the HREE).

Clear geochemical distinctions are also apparent between footwall felsic rocks and andesitic to felsic rocks in the hanging wall of deposits where detailed studies have been carried out (Golden Grove: Whitford and Ashley, 1992; Sharpe and Gemmell, 2001; Guilliamse, 2013; Mount Gibson: Yeats and Groves, 1998; Jaguar: Belford, 2010; Belford et al., submitted for publication).
A similar situation was noted in the Pilbara Craton by Vearncombe and Kerrich (1999); Figs. 9 and 12). In stark contrast to petrochemically prospective footwall sequences, hanging wall felsic rocks represent a return to ‘normal’ (i.e. non rift-related) volcanism with steep REE profiles. These hanging wall felsic rocks have geochemical characteristics typical of unprospective units worldwide (i.e. FI to FII affinities) and are characterized by significantly higher Zr/Y, Th/Yb, La/YbCN and Dy/YbCN ratios (i.e. calc-alkaline characteristics), and lower Sc/TiO2, Sc/V, HFSE and HREE contents (Fig. 9). In the Golden Grove camp hanging wall felsics at Scuddles (Fig. 14) contain both petrochemically prospective and unprospective signatures (Whitford and Ashley, 1992; Fig. 11b). Prospective signatures in the hanging wall of the Scuddles deposit are restricted to quartz-porphyritic ash flow tuffs of Scuddles Formation Member 2 (Fig. 14). However, this member in turn forms the footwall to Zn mineralization at Hougomont higher in the Golden Grove stratigraphy (Gawlinski, 2004; Fig. 14).

5.2. Comparisons to the Abitibi subprovince

In their classic review of volcanic rocks of the VHMS-rich Abitibi Subprovince, Canada, Barrie et al. (1993) identified five distinct geochemical groups; three of which are associated with VHMS mineralization (Groups I–III). Group I, associated with >50% of all VHMS deposits by tonnage, comprised ~10% of the area of volcanic terranes and included volcanic sequences at Kamiskotia, Matagami and Chibougamau. These areas are characterized by bimodal assemblages of tholeiitic basalt–basaltic andesite and high silica rhyolite with high HFSE and HREE concentrations, FlIb signatures, low LREE (La/YbCN 0.8–3) and pronounced negative Eu anomalies on chondrite-normalized REE diagrams (Barrie et al., 1993). Group II felsic rocks, host to approximately 30% of VHMS deposits in the Abitibi, are characterized more transitional tholeiitic to calc-alkalic signatures, intermediate HFSE contents and higher REE ratios (La/YbCN 1–4; FlIIa affinity; Barrie et al., 1993).
Ill rocks are limited to one deposit (Selbaie mine) and are petrochemically less prospective (i.e. FeI affinity). VHMS barren volcanic sequences of Groups IV and V are characterized by low HFSE contents (i.e. FeI affinity) and high REE ratios (La/YbCN 8–20 and 12–62 respectively) (Barrie et al., 1993).

In the Youanmi Terrane, felsic rocks similar to VHMS-rich Group I rhyolites of the Abitibi greenstone belt (e.g. Fillb affinity Kamiskotia felsics) are restricted to those which belong to the Yaloginda Formation/Kantie Mudran Volcanics Member and formed at c. 2815 Ma. These units are underlain by large mafic–ultramafic sequences and intrusive complexes related to 2.82 Ga plumber magmatism (discussed later). Rocks sampled of this age from Quinns (Austin), Copper Hills, Youanmi and Windimurra are characterized by high HREE and HFSE concentrations (Fig. 10), and display flat chondrite-normalized REE profiles (Fig. 11d). VHMS-associated felsic rocks analyzed from Golden Grove, Weld Range, Emily Well, Jiliewarra, Dalgaranga, Hollandaire and Gum Creek of the Youanmi Terrane display similar chondrite-normalized REE profiles to the Group II suite of the Abitibi greenstone belt (i.e. Noranda, Misema: Fig. 11a–e), although the latter typically displays slightly lower LREE enrichment.

Immobile-element ratios highlight subtle differences between felsic rocks of the Yilgarn Craton and Abitibi greenstone belt in Figs. 9 and 13. Felsic rocks from both areas are characterized by similar Zr/Y and La/YbCN ratios, although these range to significantly higher values in the Yilgarn – particularly from areas which lack mineralization or only contain minor Cu–Zn mineralization. Most felsic samples in the Yilgarn also display significantly higher Th/Yb values than felsic rocks from the Abitibi greenstone belt. Only the Au-rich LaRonde and Bousquet felsic rocks show similar values to barren and weakly mineralized felsic rocks from the Yilgarn Craton. This is consistent with the extended crustal recycling in the Youanmi Terrane (Champion and Cassidy, 2007; Ivanic et al., 2013; Wyche et al., 2013), and its more evolved nature compared to Abitibi crust (Huston et al., 2005, 2014). The only areas in the Yilgarn Craton which have comparable Th/Yb ratios to the Cu–Zn rich areas of Abitibi (e.g. Noranda, Matagami) are those with significant VHMS resources (Figs. 9 and 13b,d). This adds further weight to suggestions of Huston et al. (2014) that the Yilgarn may be impoverished in VHMS mineralization as only in the Cue Zone and around Teutonic Bore was the crust sufficiently juvenile.

As documented previously (e.g. Huston et al., 2005, 2014), known VHMS occurrences are relatively scarce in the Eastern Goldfields Superterrane. The recognition of bimodal volcanism in the Gindalbie Domain and tholeiitic felsic rocks was suggested to reflect the increased prospectivity of this region. According to Brown et al. (2002), the Gindalbie Domain (Fig. 1) includes both VHMS-prospective, HFSE-enriched bimodal (basalt–rhyolite) complexes (e.g. at Melita and Teutonic Bore) and largely unprospective, calc–alkaline intermediate–silicic volcanic rocks (e.g. at Spring Well and Jeedamya). Felsic volcanic complexes at Melita and Teutonic Bore were described as having elevated concentrations of SiO2, HFSE and Y (i.e. A-type, Fill characteristics), low Zr/Y and Th/Yb, and flat to slightly LREE-enriched REE profiles (with pronounced negative Eu anomalies) (Witt et al., 1996; Brown et al., 2002; Barley et al., 2008). Recent work by Belford (2010) has demonstrated the Teutonic Bore volcanic complex is not strictly bimodal due to the presence of abundant andesites in the hanging wall and footwall of mineralization at Jaguar. Significant volumes of andesite also occur at Mount Gibson (Yeats and Groves, 1998) and Hollandaire (Hayman et al., submitted for publication) and The Cup (CSIRO unpublished). The data presented here also suggest that both petrochemically favourable felsic rocks and unprospective rocks occur at Spring Well and Melita (e.g. Figs. 10, 12b–c and 13), although the former is characterized by slightly lower HREE concentrations than rocks from Jaguar. Some samples from Melita show similar geochemical signatures to Group I Abitibi felsics, although are characterized by slightly higher LREE enrichment (Fig. 10). Although

**Fig. 9.** Tukey (box and whisker) plots for felsic rocks of the Yilgarn Craton, Pilbara Craton (data from Vearncombe and Kerrich, 1999) and VHMS-bearing camps of the Abitibi greenstone belt, Canada, containing >20 Mt of ore (data from MacLean and Hoy, 1991; Mercier-Langevin et al., 2002; Gabriou and Pearson, 2008). Felsic rocks from the Yilgarn Craton are sorted into the following groups: (1) areas with no base metal mineralization (e.g. Norseman, Kambalda, Ulrich Range), (2) areas with minor Cu–Zn mineralization (e.g. Dalgaranga, Windimurra, Narndee, Chesterfield, Jungle Pool), (3) areas with significant VHMS resources (e.g. Teutonic Bore, Jaguar, Quinns, Golden Grove, Hollandaire), and (4) areas where no base metal mineralization has been identified that may VHMS prospective based on their geochemistry (e.g. Melita, Brew Well). IQR, Interquartile range.
major exploration efforts were made around Melita in the 1970s, only small sub-economic concentrations of sulphides were discovered (mostly pyrite, minor pyrrhotite, sphalerite, galena and chalcopyrite at Jungle Pool to the southeast) (Witt, 1994). Samples from south of the Jungle Pool base metal occurrence appear unprospective (e.g. low HFSE; FII affinity; not shown), though may not represent the same stratigraphic horizon. Limited trace-element data is available for these rocks. Detailed GSWA-led studies on the Nimbus and Erayinia VHMS deposits of the EGS are underway.

6. Tectonic-stratigraphic framework

6.1. Youanmi Terrane

Using the stratigraphy of Van Kranendonk et al. (2013) for the Murchison Domain (Fig. 2), and an extensive database of published U–Pb zircon ages from the Yilgarn Craton, we have recognized several episodes of VHMS mineralization in the Youanmi Terrane. The syngenetic nature of VHMS deposits means the timing of mineralization will be within error of dated footwall assemblages providing there has been no extended depositional hiatus lasting more than a few million years. Four distinct periods of VHMS mineralization have been recognized in the Youanmi Terrane at >2.9 Ga, 2.815 Ma, 2.760–2.745 Ma and 2.722 Ma (Fig. 2). VHMS-exploration should be focused on tholeiitic and HFSE-enriched felsic rocks, closely associated with mafic volcanic rocks and argillaceous sedimentary rocks (particularly graphitic shales).

Two areas that produced much of Western Australia’s Cu and Zn ore (Golden Grove and Ravensthorpe) formed prior to 2.9 Ga. In the c. 2.96–2.93 Ga Golden Grove camp significant Cu–Zn resources occur at Gossan Hill, Scuddles, at various depths between the two deposits (e.g. Amity, Ethel), and at Gossan Valley-Felix (Table 1). The 3.0–2.95 Ga Ravensthorpe Greenstone belt accounted for much of Western Australia’s historic Cu production (Marston, 1979). Cu–Au and Cu–Zn mineralization is primarily hosted in the Annabelle Volcanics (2989 ± 11 Ma) within 2 km from the contact of the synvolcanic Manyutup Tonalite (2985 ± 12 Ma and 2989 ± 7 Ma) (Witt, 1999). Additional VHMS-style base metal mineralization which formed prior to 2.9 Ga has been recognized at Weld Range (2969 ± 3 Ma: Wingate et al., 2008a; 2979 ± 3 Ma: Wingate et al., 2012c; also see Guillianse, 2013), in the Tallering Greenstone belt
(2935 Ma ± 2 Ma: Pidgeon and Wilde, 1990), Twin Peaks Greenstone belt (c. 3014 Ma: Pidgeon and Wilde, 1990) and at Mt. Gibson (c. 2.93 Ga: Yeats et al., 1996). New GSWA field mapping around Golden Grove and U–Pb geochronology aims to refine the >2.9 Ga stratigraphy of the Yalgoo-Singleton greenstone belt and Murchison Domain as a whole.

Detailed stratigraphic work around Golden Grove has documented the role of at least local extension and the presence of synvolcanic faults (Clifford, 1992; Sharpe and Gemmell, 2000). The VHMS-bearing Golden Grove Formation is characterized by the products of distal explosive felsic volcanism, re-deposited by successive mass flow processes (Sharpe and Gemmell, 2000). Six members have been identified (Fig. 14) and the absence of members GG2 and GG3 at Gossan Hill has been suggested to reflect a local depositional hiatus caused by uplift along syn-depositional structures (Sharpe and Gemmell, 2000). The upper parts of the formation reflect a waning of sediment influx, with unit GG6 (which hosts the bulk of mineralization) representing ambient background sedimentation (Sharpe and Gemmell, 2002). The overlying Scuddles Formation consists of quartz-feldspar phryic rhyodacite overlain and intruded by feldspar-quartz phryic dacite. Dacite also intrudes members GG4–GG6 of the underlying Golden Grove Formation (Fig. 14) and is interpreted to be an intrusive/extrusive dacite dome that overlies its discordant volcanic feeder (Sharpe and Gemmell, 2000). The contact between unit GG6 and the Scuddles Formation therefore records the onset of proximal felsic volcanism in the area and further geodynamic change in the basins evolution. The position of original synvolcanogenic structures at Gossan Hill are highlighted by the: (i) asymmetry of massive sulfides, massive magnetite and stringer zones relative to the volcanic feeder for the Scuddles Formation dacite; (ii) a decreasing thickness of massive sulfide, magnetite and stockwork southwards from discordant contact of the hanging wall dacite; and (iii) the widest variation in δ34S occur at the southern end of the Gossan Hill orebody (Sharpe and Gemmell, 2000).

Following an extended depositional hiatus and a major plume event at c. 2.82 Ga (Ivanic et al., 2010), a second period of VHMS mineralization occurred in the Youanni Terrane between c. 2818 and 2813 Ma. In the c. 2825–2805 Norie Group, VHMS mineralization occurs at Quinns (2817 ± 3 Ma: Wingate et al., 2011a), Just Desserts (c. 2813 Ma, discussed in Hassan, 2014) and Chunderloo associated with petrochemically prospective felsic rocks of the Yalaginda Formation. The Yalaginda Formation is characterized by tholeiitic to transitional felsic rocks with flat REE profiles and HFSE enrichment (Van Kranendonk et al., 2013; Figs. 10 and 11d). Geochemically similar felsic rocks also host significant VHMS mineralization overlaying the large 2815–2800 Ma igneous complexes of the central Youanni Terrane (Boodanoow and Meelne suites: Figs. 2 and 4) in the Kantee Murdiana Volcanics Member (Fig. 11d). Base metal occurrences have been identified in supracrustal sequences associated with all of these igneous complexes (Fig. 4): Narndee, Youanni, Windimurra, Barrambie
and Lady Alma (Figs. 1 and 4). U–Pb zircon geochronology on supracrustal rocks at Windimurra (2813 ± 3 Ma: Nelson, 2001b) and Youanmi (2814 ± 14 Ma: Nelson, 2002) are within error of the VHMS-bearing felsic rocks of the Yaloginda Formation. Dating of an andesite from a greenstone belt adjacent to the Narndee Igneous Complex, has yielded a similar but older age (2818 ± 3 Ma: Wingate et al., 2012b), most likely representative of the Nore Group host rocks into which the complex intruded at c. 2800 Ma. The Windimurra Igneous Complex has a true thickness of at least 6 km and covers an area of 2500 km². This voluminous layered intrusion, along with other anhydrous Meeline Suite intrusions such as Youanmi Igneous Complex is thought to represent a major, high-temperature mantle melting event at c. 2815 Ma (Ivanic et al., 2010). Pyroxene geobarometry suggest the Windimurra Igneous Complex was emplaced at mid-crustal depth (≥400 MPa: Ahmat, 1986). Pressure estimates from the younger and smaller Narnde Igneous Complex indicate it was emplaced at 3–10 km depth (100–300 MPa: Scowen, 1991). Petrochemical signatures (F1–F1c characteristics) of the Yaloginda Formation felsic rocks which host VHMS mineralization are consistent with shallow-melting of tholeiitic mafic substrate with variable degrees of crustal contamination. Coeval HFE-enriched felsic intrusions around Narnde, Windimurra and Youanmi (Fig. 4) are represented by the Mt. Kenneth Suite (Figs. 2 and 4) and display similar geochemical characteristics to the Yaloginda Formation and Kaitie Murdiana Volcanics Member (Ivanic et al., 2012) (see Fig. 11d). It has been suggested by Ivanic et al. (2010) the large ultramafic–mafic intrusions of the Meeline and Boodanoo suites were emplaced across the northern Youanmi Terrane into a rift-zone marked by younger NdDM model ages (the ‘Cue Zone’ of Huston et al., 2014; Fig. 3). Mole et al. (2014) recently presented Nd isotope evidence that pre-existing 3.7–3.5 Ga crust was initially rifted in the Cue Zone at c. 3.0 Ga, thinning the crust and extracting new material from the mantle. The authors linked this event to the extraction of the Lake Johnston block (i.e. southern part of the Southern Cross Domain) and Burtville Terrane crust from the mantle. A plume–event at this time is evident from 3.0 Ga Southern Cross Domain komatiites (references in Mole et al., 2014). During the subsequent 2.82 Ga plume event, the Cue Zone was reactivated and preexisting structural weaknesses provided sites for magmatism to rise to relatively shallow crustal levels (Ivanic et al., 2010). The shallow emplacement of these large intrusions likely facilitated hydrothermal circulation in the upper crust.

In the 2800–2735 Ma Polelle Group of the Murchison Domain, VHMS mineralization has been recognized in the Greensleeves Formation at Hollandaire (2.8 Mt at 1.6% Cu, 5 g/t Ag and 0.4 g/t Au), Mt. Mulcahy, Emily Well and in the Dalgaranga greenstone
belt. Minor base metal mineralization also occurs at Chesterfield, Abbotts, Cullculli and around Meekatharra (Figs. 1 and 4). Areas of the Greensheets Formation which contain petrochemically prospective felsic rocks host Cu–Zn mineralization, whereas petrochemically unprospective areas are barren and record normal ‘subduction affinity’ magmatism characterized by steep (TTG-like) REE profiles and pronounced negative Nb anomalies (e.g. Wyman and Kerrich, 2012; Van Kranendonk et al., 2013). U-Pb zircon geochronology from NW of Hollandaire (Elya Hill) has yielded an age of 2746 ± 4 Ma (Wingate et al., 2012a), within error of ages obtained from the Dalgaranga greenstone belt (2745 Ma; Pidgeon and Hallberg, 2000), Mt. Mulcaby (nearby intrusion – 2748 ± 5 Ma; Wingate et al., 2010a), Chesterfield (2747 ± 5 Ma; Wingate et al., 2012d), and Abbotts (north of the Conroy occurrence – 2739 ± 10 Ma; Wingate et al., 2008b). More recently, an age of c. 2759 Ma has been obtained from drill core at Hollandaire (Hayman et al., submitted for publication), almost identical to an age from volcanic succession near Emily Well (c. 2761; Pidgeon and Hallberg, 2000). Both TTG-like (Cullculli suite) and HFSE-enriched (Elya suite) felsic intrusions occur at this time (Fig. 2). The Elya Suite is most extensive around Hollandaire and Dalgaranga (Fig. 4) and displays similar geochemical characteristics to VHMS-associated felsic rocks of the Greensheets Formation (Ivanic et al., 2012) (see Fig. 11e).

Finally, VHMS mineralization in the 2735–2700 Ma Glen Group occurs in the Gum Creek greenstone belt (e.g. The Cup, Bevan, Blind Bat, Eds Bore) associated with felsic volcanic rocks and graphitic/carbonaceous sedimentary rocks. Felsic volcanic rocks near the Bevan base metal occurrence have yielded an age of 2722 ± 6 Ma (Bodorkos et al., 2006). The emplacement of thick differentiated mafic–ultramafic sills of the Yalgowra Suite into shallow levels of the crust at this time may have driven hydrothermal circulation (Figs. 2 and 13). The cumulative thickness of the Yalgowra Suite is ~1 km (Wyche et al., 2013); its age is constrained by U–Pb dates of 2735 ± 5 Ma, 2719 ± 6 Ma, and 2711 ± 2 Ma (Ivanic et al., 2010). The Montague granodiorite (2722 ± 7 Ma; Wang et al., 1998) is both spatially and temporally associated with VHMS mineralization in the Gum Creek greenstone belt. Its geochemical affinity is similar to nearby felsic rocks (Fig. 11f) which includes both unprospective (F1 affinity) and prospective (F2 affinity) units (Figs. 10 and 11f).

6.2. Kalgoorlie and Kurnalpi terranes

Although there are a number of synvolcanic base metal occurrences in the Eastern Goldfields Superterrane (e.g. Teutonic Bore camp, Jungle Pool, Nimbus, Anaconda, Erayinia), the timing of mineralization at several of these localities is not well constrained. In the northern Gindalbie Domain significant VHMS mineralization occurred at c. 2690 Ma in the Teutonic Bore camp (2688 ± 4 Ma: Pidgeon and Wilde, 1990; 2692 ± 4 Ma: Nelson, 1995) and is associated with felsic volcanic complexes and deep-marine, argillaceous sedimentary rocks (Belford, 2010; Belford et al., Submitted). Mafic rocks with BABB-like geochemical characteristics stratigraphically overly and intrude VHMS mineralization at Jaguar (e.g. Belford, 2010), and host VHMS mineralization at Teutonic Bore. U–Pb zircon geochronology from the Jeedamy Complex and Melita Complex (Fig. 5) have produced similar, albeit slightly younger, ages of...
2681 ± 4 Ma (Nelson, 1997) and 2683 ± 2.4 Ma (Brown et al., 2002) and may constrain the timing of minor base metal mineralization at Jungle Pool. A similar age has also been obtained from 4 km along strike of the Erayinia/King VHMS occurrence (2680 ± 5 Ma: Wingate and Bodorkos, 2007a).

Unlike VHMS-associated felsics at Teutonic Bore, at Anaconda there is a close temporal and spatial association between felsic volcanic rocks and spinifex-textured komatiitic flows. Together with an age of 2698 ± 5 Ma (Nelson, 2005), this suggests VHMS mineralization at Anaconda is hosted within an older volcanic sequence than those of the northern Gindalbie Domain (Fig. 5). Constraining the timing of VHMS mineralization at Nimbus, Brilliant Well, Rungine and Balagundi requires additional U–Pb geochronology. Regardless, VHMS mineralization in the Eastern Goldfields Terrane is clearly younger than the last period of mineralization in the Youanmi Terrane (c. 2722 Ma).

Five clans of HFSE-enriched granitic rocks have been identified in the Eastern Goldfields Superterran by Cassidy and Champion (2002) and Champion and Cassidy (2002) which have clear spatial and temporal associations to areas of VHMS mineralization (Fig. 6), as in the Youanmi Terrane (Figs. 2 and 4). HFSE-enriched granites were characterized by a distinct geochemistry of high FeO, MgO, TiO₂, Y and Zr, with low Rb, Pb, Sr and Al₂O₃, and the presence of biotite and/or amphibole in quartz and feldspar rich rocks (Champion and Cassidy, 2002). Clans were defined on similar petrographic and geochemical characteristics (see Cassidy and Champion, 2002), and may be subdivided into supersuites and suites. U–Pb zircon age constraints are only available for a limited number of supersuites, summarized in Fig. 5. The Kookynie Clan includes the Penzance Supersuite (exposed near the Jungle Pool base metal occurrence), Kookynie Supersuite (exposed east of Teutonic Bore) and the Boo Boo and Gearless intrusions of the northern Kalgoorlie Terrane (Fig. 6). U–Pb ages of c. 2680 Ma for the Kookynie and Penzance supersuites (Fig. 5) are comparable to ages obtained from Jeedamya, Melita, Erayinia and the timing of mafic intrusive across the EGS (2680 ± 8 Ma; 2687 ± 5 Ma: references in Ivanic et al., 2010). Geochemically, these intrusive rocks are similar to felsic rocks associated with VHMS mineralization at Teutonic
Bore (Fig. 12h). The Bullhead Supersuite exposed east of Teutonic Bore may also be of similar age as it has similar geochemical characteristics (Fig. 12h). The Satisfaction Supersuite is restricted to the eastern side of the northern Kalgoorlie Terrane (Fig. 6) and shows a strong spatial relationship with contemporaneous (and in part co-genetic) felsic volcanic rocks (Champion and Cassidy, 2002). Between 70 and 130 km SW of Anaconda, the Outcamp Bore Supersuite occurs as a linear belt of foliated granitic rocks and dykes, internal to the greenstone sequences, ranging in composition from biotite monzogranite to tonalite (Champion and Cassidy, 2002). Ages from c. 2719 to 2698 Ma are within error of the Minerie and Kurnalpi sequences of the EGS (Fig. 5) and U–Pb zircon geochronology from Anaconda (2698 ± 5 Ma: Nelson, 2005).

6.3. Burtville and Yamarna terranes

As previously discussed, the Burtville Terrane shares many features of the Youanmi Terrane (e.g. Pawley et al., 2012). Rocks of similar age to the first three periods of VHMS mineralization in the Youanmi Terrane occur in the Burtville Terrane at c. 2.97 Ga (Ulrich Range greenstone belt), c. 2805 Ma (Duketon greenstone belt), c. 2775–2755 Ma (Laverton, Irwin Hills-Stella Range and Mount Venn greenstone belts) (Supplementary Fig. 1; Pawley et al., 2012). Samples herein although limited to three areas (Fig. 12f) display steep REE profiles and are generally considered unprospective for VHMS mineralization. Although the Burtville Terrane is isotopically more juvenile than the Youanmi Terrane (even moreso than the Cue Zone) and would therefore appear VHMS prospective, this simply reflects its younger mantle extraction age (c. 3.0 Ga: Pawley et al., 2012). No areas equivalent to the Cue Zone have been documented in the Burtville Terrane, except some single point anomalies characterized by slightly younger Nd\(_{\text{DM}}\) ages (Fig. 3). These areas reflect the introduction of juvenile material between 2940 and 2755 Ma, most likely at 2810–2750 Ma associated with c. 2.82 Ga plume magmatism (e.g. Swincer Dolerite) (Mole et al., 2014). As the 2.82 Ga plume event in the Youanmi Terrane was particularly favourable for VHMS mineralization, felsic rocks in these areas may be prospective. In the Youanmi Terrane, VHMS prospective felsic rocks may also occur in close proximity to unprospective units in the >2.9 Ga (Ulrich Range) and c. 2.76 Ga (Laverton, Irwin Hills-Stella Range, Mount Venn) greenstone belts. Additional geochemistry from these areas is recommended.

Although data is limited for the Yamarna Terrane, Nd isotope analyses suggest the crust was extracted from the mantle at c. 2950–2850 Ma (Mole et al., 2014). Felsic rocks included herein are limited to samples from Mount Gill, which display similar geochemical characteristics to VHMS bearing rocks at Teutonic Bore and Jaguar (Fig. 12a and f). U–Pb zircon geochronology constrains the sequence to 2683 ± 5 Ma (Pawley et al., 2012), within error of dated assemblages at Melita and Erayinia, and slightly younger than Teutonic Bore. This area is considered prospective for VHMS mineralization.

6.4. South West Terrane

Base metal mineralization in the South West Terrane is restricted to the older c. 3.0–3.2 Ga sequences, with the Balin-gup Metamorphic Belt hosting the Wheatley deposit, the Wongan Hills Greenstone belt hosting the Mystery and associated base metal occurrences, and the Jimperding Metamorphic Belt associated with minor intercepts of base metal mineralization at Ularring Rock, Southern Brook, Ablett, Chapman and Dasher (MINEDEX). No base metal occurrences have been identified in the younger 2715–2675 Ma Saddleback and Moranup greenstone belts (Fig. 1).

U–Pb zircon geochronology on a ‘psammite’ in the footwall of the minor Zn–Cu mineralization at Wheatley (GA sample ID 2004968001A) yielded a maximum depositional age of 2646 Ma, with a spread of ages from ~2600 to 2700 Ma (Sircome et al., 2007). The meaning of this age is not clear.

7. Conclusions

Using an extensive database of compiled whole-rock geochemistry, and recently published U–Pb and stratigraphic constraints, recognized VHMS occurrences from across the Yilgarn Craton have been placed in a detailed tectono-stratigraphic framework. VHMS mineralization in the Yilgarn Craton is preferentially associated with areas of thinned, juvenile crust as revealed by Nd and Pb regional isotope variations (e.g. Huston et al., 2014). Prospective host sequences can be identified through the presence of: largely bimodal volcanic complexes (although anodesites do occur), syn-volcanic faults, HFSE- and HREE-enriched synvolcanic intrusions, regional isotope signatures indicative of rifting, and specific petrochemical signatures.

In terms of petrochemical signatures, VHMS-bearing felsic rocks in the Youanmi Terrane and Eastern Goldfields are characterized by low Zr/Y, La/Yb and Th/Yb ratios, high Sc/TiO\(_2\), HFSE and HREE contents, and flat HREE profiles. Chondrite-normalized REE profiles for felsic rocks overlying 2.82–2.80 Ga plume-related basaltic and large igneous complexes of the Youanmi Terrane are flat. Other VHMS-bearing felsic rocks are characterized by slight LREE enrichment (La/Sm\(_{\text{CN}}\) < 3) and flat HREE profiles (Dy/Yb\(_{\text{CN}}\) ~ 1 or less).

In the South West Terrane VHMS mineralization is preferentially associated with older c. 3.0–3.2 Ga greenstone sequences. In the Youanmi Terrane four distinct periods of economic mineralization can be recognized: (i) >2.9 Ga, associated with early bimodal-mafic greenstone belts (e.g. Golden Grove, Ravensthorpe, Twin Peaks) subjected to extension; (ii) c. 2815 Ma, following a major plume event and coeval with the emplacement of large igneous complexes across the northern Youanmi Terrane at shallow levels in the crust (e.g. Austin, Youanmi, Narndee, Windimurra); (iii) 2760–2745 Ma, in areas of rift-related magmatism during the deposition of the Greensleeves Formation (e.g. Hollandaire, Dalgaranga, Mt. Mulcahy); (iv) c. 2725 Ma, in the Gum Creek Greenstone belt (e.g. The Cup, Bevan) during a second major plume-event, coeval with the emplacement of high-level sills. Subsequently, VHMS-mineralization occurred in the Eastern Goldfields Supergroup where it was also closely associated with HFSE-enriched synvolcanic intrusions. The mineralization is apparently restricted to areas of juvenile crust and largely bimodal complexes which formed between c. 2700 and 2680 Ma (e.g. Teutonic Bore, Erayinia, Nimbus).

More data is required in the South West, Burtville and Yamarna terranes, and a number of greenstone belts of the Youanmi Terrane (e.g. Twin Peaks, Tallering) in order to clearly delineate regions of prospectivity and establish temporal, geochemical and stratigraphic associations to mineralization. Localized studies are required in order to establish volcanicological settings for a number of deposits and their controlling factors.

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Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2014.11.002.

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