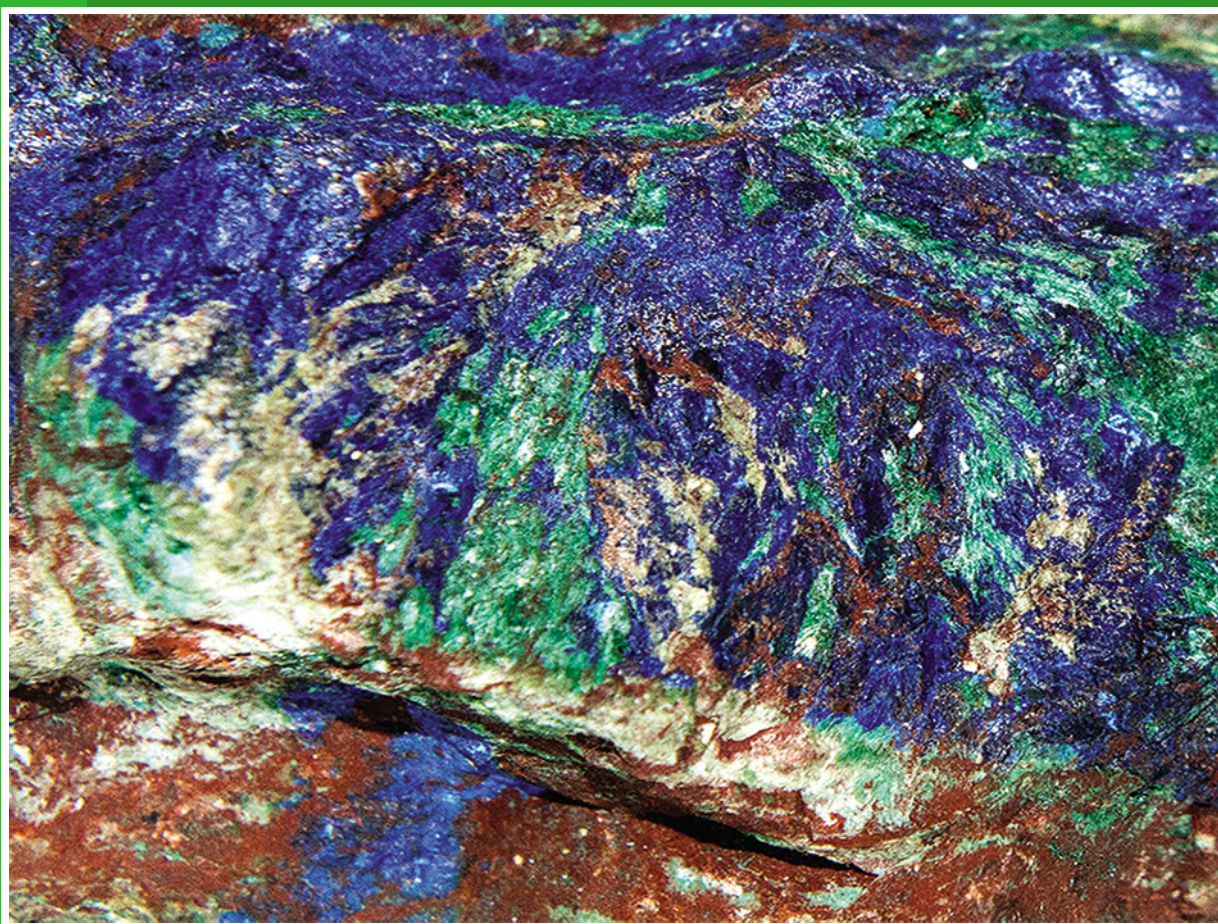


REPORT  
165

# VMS MINERALIZATION IN THE YILGARN CRATON, WESTERN AUSTRALIA: A REVIEW OF KNOWN DEPOSITS AND PROSPECTIVITY ANALYSIS OF FELSIC VOLCANIC ROCKS

by SP Hollis, CJ Yeats, S Wyche, SJ Barnes, and TJ Ivanic





Government of **Western Australia**  
Department of **Mines and Petroleum**

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**Cover photograph:** Azurite and malachite from the Mount Desmond area southeast of Ravensthorpe in the southern Yilgarn Craton

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# VMS mineralization in the Yilgarn Craton, Western Australia: a review of known deposits and prospectivity analysis of felsic volcanic rocks

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## Abstract

Understanding the tectono-stratigraphic relationships of VMS deposits in greenstone sequences and the prospectivity of individual units greatly improves the effectiveness of greenfields exploration. This report describes all known, major VMS occurrences in the Yilgarn Craton using published literature and publicly available company reports. Areas of potential interest for mineral exploration have been identified based on petrochemically favourable intermediate and felsic volcanic rocks.

Prospective host sequences for VMS mineralization in the Yilgarn Craton can be identified through the presence of: largely bimodal volcanic complexes, synvolcanic faults, HFSE-enriched synvolcanic intrusions, regional isotope variations indicative of rifting (e.g. Nb, Pb, Hf), and specific petrochemical signatures indicative of shallow crustal melting. Episodes of volcanic quiescence at or near the ore horizon (represented by chert, black shale or banded iron-formation) are a common feature of nearly all VMS occurrences in the Yilgarn Craton. Four distinct periods of economic mineralization and petrochemically favourable felsic rocks can be recognized in the Youanmi Terrane in the western part of the craton: 1) >2900 Ma, associated with early bimodal–mafic greenstone belts; 2) c. 2815 Ma, following a major plume event and coeval with the emplacement of large igneous complexes; 3) 2760–2745 Ma in areas of rift-related magmatism; and 4) c. 2725 Ma during a second major plume-event. In the Eastern Goldfields Superterrane, in the eastern part of the craton, VMS mineralization is closely associated with HFSE-enriched synvolcanic intrusions, and is predominantly restricted to areas of juvenile crust and bimodal complexes that formed between 2700 and 2680 Ma. In the South West Terrane, in the southwestern part of the craton, VMS mineralization is preferentially associated with older, 3000–3200 Ma, greenstone successions.

**KEYWORDS:** Archean, base metals, greenstone, volcanogenic deposits, volcanic hosted deposits

## Introduction

The Archean Yilgarn Craton of Western Australia is a world-class metallogenic province, hosting considerable resources of gold, Ni-sulfides and iron ore (Fig. 1a). Despite isolated successes in the 1970s, such as the discovery of significant orebodies at Golden Grove and Teutonic Bore, exploration for volcanogenic massive sulfide (VMS) mineralization waned through most of the 1980s and 1990s (Yeats, 2007). Historically, there have been several major hindrances to VMS exploration in the Yilgarn Craton. The Yilgarn is characterized by a paucity of outcrop, deep weathering and oxidation, and high strain (McConachy et al., 2004). Although deep weathering in Australia increases the economics of some

deposits (e.g. Nimbus, Hollandaire), a poor understanding of regolith processes until recent decades has meant it often hindered exploration efforts. Furthermore, saline groundwater can overwhelm EM (electromagnetic) responses (Phillips, 2004) which, combined with deep weathering, conductive overburden and intercalated black shale horizons in prospective successions, has meant few deposits have been discovered using standard geophysical techniques.

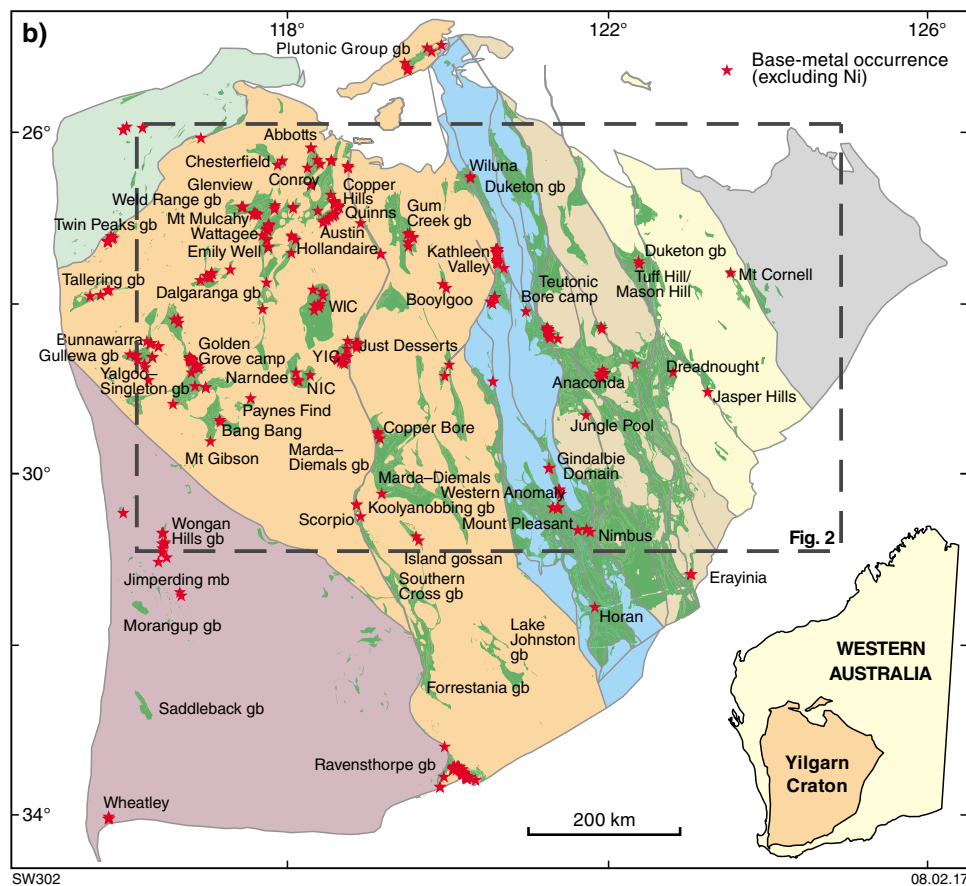
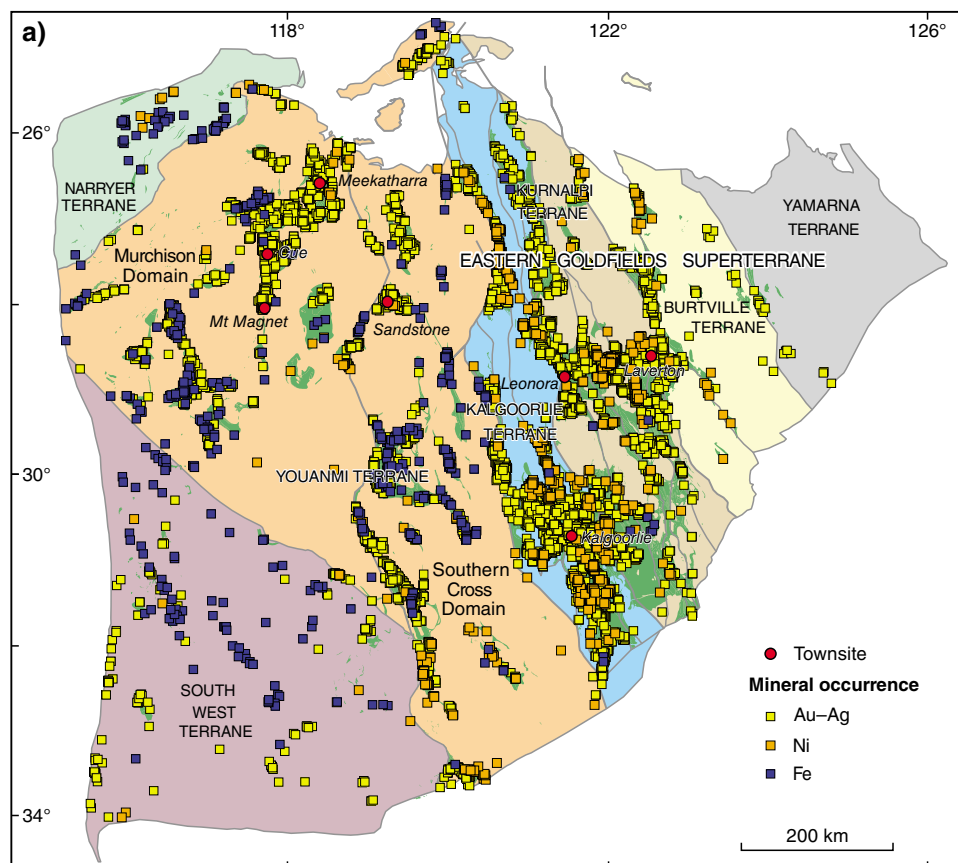
Renewed exploration activity in the last 15 years has led to a number of new VMS discoveries, including further successes at Golden Grove, Nimbus and Manindi (Freddie Well), and new resources at Jaguar, Bentley, Austin, Just Desserts and Hollandaire (Table 1). VMS mineralization has also been identified at sites across the Yilgarn Craton, such as Wheatley, Narndee, Mount Mulcahy, The Cup, Southern Gossan, Erayinia/King and Conquistador, although some of these were originally discovered during earlier exploration efforts. Over 500 base metal occurrences (excluding those associated with nickel) have now been identified in the Yilgarn Craton (Fig. 1b). These successes are primarily due to advances in a number of fields, outlined below.

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**Figure 1.** (opposite) a) Major subdivisions of the Yilgarn Craton, Western Australia, showing the distribution of greenstone belts, and precious-metal, Ni and Fe occurrences (GSWA, 2014a, 2015a,b). Terrane and domain subdivisions are based on Cassidy et al. (2006), Barley et al. (2008) and Pawley et al. (2012); b) base metal occurrences in the Yilgarn Craton exclude Ni and are from GSWA (2015b). Significant base metal occurrences and greenstone belts referred to in the text are labelled. NIC, Narndee Igneous Complex; WIC, Windimurra Igneous Complex; YIC, Youanmi Igneous Complex; gb, greenstone belt

**Table 1.** VMS resources in the Youanmi Terrane and Eastern Goldfields Superterrane, Yilgarn Craton. Adapted from McConachy et al. (2014). Resource references in Hollis et al. (2015)

<i>Terrane</i>	<i>Domain</i>	<i>Age (Ma)</i>	<i>Deposit</i>	<i>Year of discovery</i>	<i>Mt</i>	<i>Cu (%)</i>	<i>Zn (%)</i>	<i>Pb (%)</i>	<i>Ag (g/t)</i>	<i>Au (g/t)</i>
Youanmi	Murchison	2960–2930 [Golden Grove camp]	Gossan Hill	1971	15.9	2.6	1.5	0.2	21	0.6
			Scuddles	1979	<sup>(a)</sup> 10.5	1.2	11.7	0.8	89	1.1
			Amity	1999	1.91		15.1	1.4	93	2.0
					0.25					10
			Hougoumont	1999	0.56		21.5	7.5	305	6.2
					1.49		14.6	2.1	89	2.0
				Catalpa	1999	0.63		15.5	1.6	185
			Ethel	2000	0.45		20.7	2.5		5.8
			Xantho	2003	0.4		11.9			
			Cambewarra	2003	0.14		13.3			
			Gossan Valley/ Felix	1971–1972	1.5		7.9		10	0.9
				1979	1.3	2.3			14	0.3
		c. 2930	Mt Gibson	1975	25.9					1.94
		c. 2746	Hollandaire	2011	2.8	1.6			5	0.4
		c. 2718	Austin (Quinns)	2008	1.48	1.02	1.39		3.31	0.24
		c. 2814	Manindi (Freddie Well)	1972	1.35	0.25	6.04		3.4	0.25
		c. 2815?	Mount Mulcahy	Historic	<sup>(b)</sup> 0.25	3.77	2.75			
	Southern Cross	c. 2813	Just Desserts	2007–2008?	1.07	1.82				0.8
		c. 2950	Kundip	-	8.94	0.3			2.3	2.7
	Kurnalpi	Gindalbie	c. 2690 [Teutonic Bore camp]	Teutonic Bore	1976	<sup>(c)</sup> 1.68	3.5	10.7		140
Jaguar				2002	<sup>(a)</sup> 1.60	3.1	11.3	0.7	115	
Bentley				2008	<sup>(d)</sup> 3.05	2.0	9.8	0.6	139	0.7
Murrin		c. 2700	Anaconda	Historic	Historic Cu production (4595 t)					
Kalgoorlie	Boorara	c. 2700?	Nimbus	1993	4.88		1.33		79	0.29

**NOTES:**

(a) Pre-mining reserve

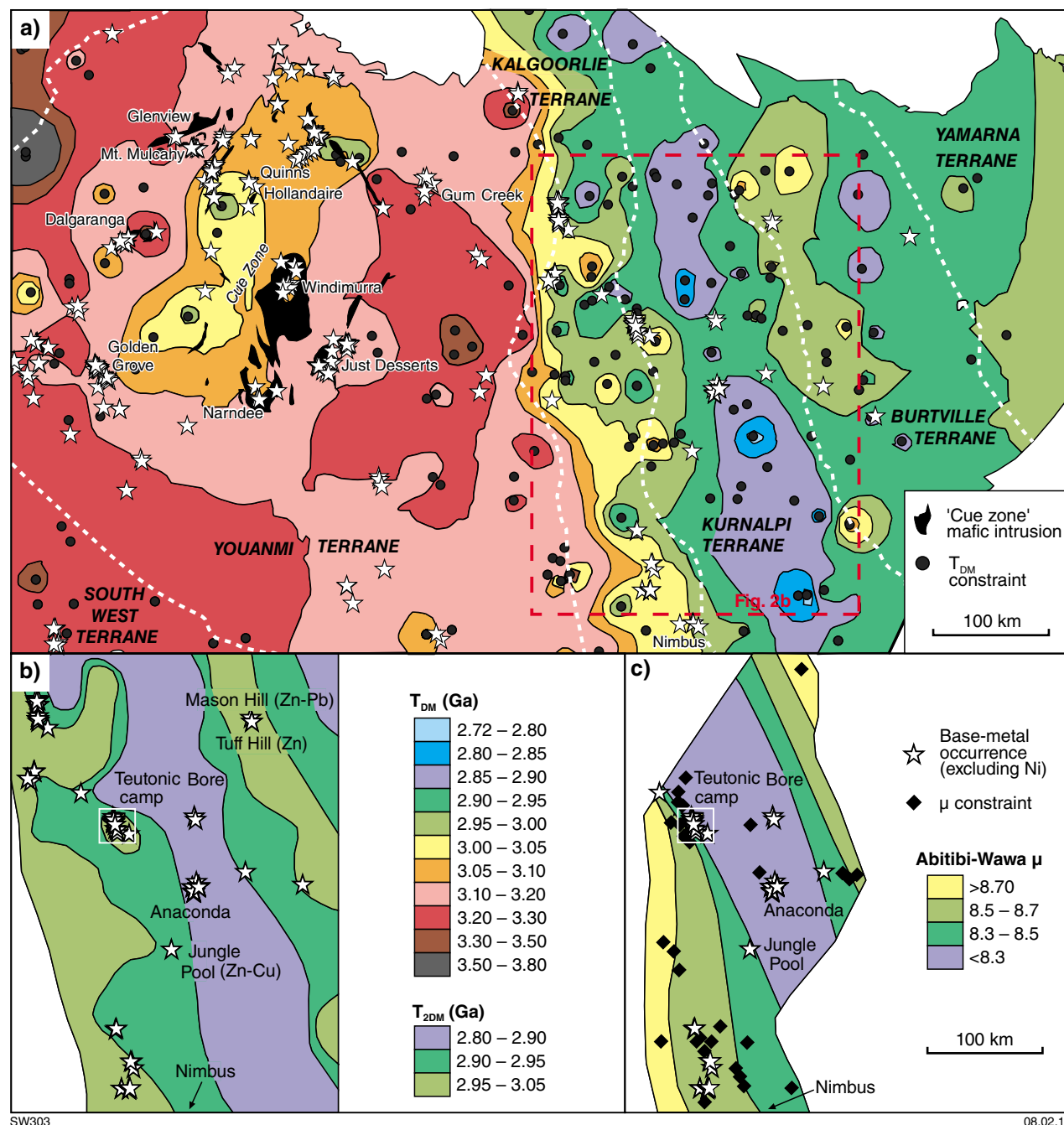
(b) Assumes a minimum true thickness of 52 m and cutoff of 2.5% Cu

(c) Production to end 1984

(d) Pre-mining resource (indicated + inferred)



- Our understanding of the geology of the Yilgarn Craton has greatly improved in recent decades, through a combination of airborne magnetic surveys, detailed follow-up mapping, greatly expanded geochronology and isotope terrane delineation (e.g. Champion and Sheraton, 1997; Cassidy et al., 2006; Champion and Cassidy, 2007; Czarnota et al., 2010; Ivanic et al., 2010, 2012; Van Kranendonk et al., 2013; Huston et al., 2014; Mole et al., 2014, 2015). Good stratigraphic control is essential for VMS exploration as many VMS deposits are typically clustered along well-defined stratigraphic horizons associated with episodes of extension (e.g. Golden Grove, Teutonic Bore – Jaguar – Bentley; Clifford, 1992; Belford et al., 2015). The recognition of VMS-prospective stratigraphic horizons and common lithological and petrochemical associations (e.g. argillaceous sedimentary rocks, rift-related basalts, and high field strength element (HFSE)-enriched felsic rocks) can assist in the discovery of mineralization elsewhere in the craton. Through the use of lead, neodymium and hafnium isotopes, major metallogenic events and inherited rift-related crustal structures can be recognized (e.g. McConachy et al., 2004; Huston et al., 2005; Champion and Cassidy, 2007; Huston et al., 2014). For example, using neodymium isotope data, Huston et al. (2005) identified a 100 km-wide north-northwesterly trending zone of significantly younger Sm–Nd  $T_{2DM}$  model ages in the Eastern Goldfields Superterrane (the Kurnalpi Zone) associated with significant VMS mineralization along its margins (e.g. Teutonic Bore camp, Anaconda, Jungle Pool, Tuff Hill, Mason Hill; Fig. 2). Similar anomalous zones of young Sm–Nd  $T_{2DM}$  model ages correspond with VMS-bearing greenstone successions in the Murchison Domain (the Cue Zone in Fig 2a; Champion and Cassidy, 2007; Huston et al., 2014).
- An improved understanding of regolith processes (e.g. Smith, 2003; Cornelius and Anand, 2004; Butt, 2004; Anand and Butt, 2010) and Yilgarn groundwater chemistry (Gray, 2001; Gray et al., 2009; Noble et al., 2010) has provided new techniques to assist in VMS discoveries. The recognition of distinct groundwater compositions in different parts of the Yilgarn Craton (e.g. Gray, 2001) was crucial as groundwater chemistry will affect both the concentrations of copper and zinc, and the array and concentrations of pathfinder elements. For example, arsenic, antimony, molybdenum and tungsten are low in acidic groundwaters typical of the southern Yilgarn Craton, but increase in concentration at pH values >6.5 (Anand and Butt, 2010). Major regolith developments in the past 25 years (see review by Anand and Butt, 2010) include: 1) a greater understanding of the mobility of metals in transported and in situ regolith; 2) appropriate sampling media for VMS exploration (e.g. laterite, lag, calcrete and now biota; Wakelin et al., 2012); 3) laterite style, distribution and geochemistry across the craton (e.g. Cornelius et al., 2007); and 4) the transport of gossan fragments into cover (e.g. Butt, 2004). Regolith studies conducted over a number of deposits have identified geochemical halos associated with mineralization (e.g. Smith and Perdrix, 1983; Smith, 2003; Smith and Singh, 2007). For example, a study of pisolithic laterite in the Golden Grove camp identified pronounced antimony and bismuth anomalies over both the Gossan Hill and Scuddles deposits (see Smith and Perdrix, 1983).
- In the last 25 years, major advances have been made in petrochemical (Leshner et al., 1986; Piercey et al., 2001; Hart et al., 2004; Piercey, 2011) and lithogeochemical VMS exploration (e.g. element mobility). This is partly due to the routine application and increasingly low cost of multi-element ICP-MS geochemistry, which has allowed exploration companies to plan drilling campaigns based on the identification of VMS favourable host successions and hydrothermal assemblages. A number of workers have suggested the Gindalbie Domain of Cassidy et al. (2006) is a prospective target for VMS deposits, as south of Spring Well through Teutonic Bore to the Melita and Jeedamy volcanic areas, the greenstone successions become largely bimodal, dominated by basalt and high silica rhyolite, with lesser andesite (Witt et al., 1997; Brown et al., 2002). The immobile element ratios and REE patterns for felsic rocks from these areas (Barley et al., 2008; Belford, 2010) are similar to ‘fertile’ VMS-bearing lithologies of the Superior Province, Canada (Hollis et al., 2015). Fertile felsic rocks also occur farther south in the Kurnalpi rift zone at Erayinia (Fig. 1), opening up new areas for VMS exploration.
- Hyperspectral techniques have now been applied to a number of deposits and prospects across the Yilgarn Craton: Golden Grove (Guilliamse, 2014), Teutonic Bore (Roache, unpublished work for CSIRO–GSWA), Yuinmery (Hassan, 2014), Quinns/Austin (Duuring et al., 2016), Nimbus (Hollis et al., 2016a), Erayinia (Hollis et al., 2016b), Glenview (Guilliamse, 2014). Systematic variations in chlorite, white mica and carbonate chemistry represent powerful vectors to mineralization in a number of VMS districts worldwide (e.g. McConachy and McInnes, 2004; Yang et al., 2011; van Ruitenbeek et al., 2012).
- An increased understanding of the expression of metamorphosed VMS systems (e.g. Bonnet and Corriveau 2007; Galley et al., 2007 and references therein) has led to the identification of VMS-associated hydrothermal assemblages across the Yilgarn Craton. Metamorphic grade varies across the craton (from greenschist to granulite), and is generally higher in the southeast, closer to greenstone margins, and within narrower greenstone belts. A number of deposits across the Yilgarn Craton have been metamorphosed to relatively high metamorphic grades (e.g. King, Wheatley, and Hollandaire). For example, VMS mineralization at Kingsley (the Wheatley prospect, South West Terrane) is hosted at a transition between quartz–feldspar–biotite gneiss and amphibole–biotite–feldspar amphibolites, marking a shift from felsic to mafic volcanism (Yeats, 2007). Footwall alteration assemblages include Na-depleted, quartz–garnet–biotite–sillimanite–staurolite schists believed to represent a metamorphosed hydrothermal system (Yeats, 2007).



**Figure 2.** Regional Nd and Pb isotope variations of the Yilgarn Craton: a) Nd-depleted mantle model ( $T_{2DM}$ ) age map of the northern Yilgarn Craton (after Champion and Cassidy 2007; Czarnota et al., 2010). Terrane boundaries and base metal localities as in Figure 1a; b)  $T_{2DM}$  map of Huston et al. (2014) for the central Kalgoorlie and Kurnalpi Terranes – box of Figure 2a; c)  $\mu$  map of Huston et al. (2014) for the central Kalgoorlie and Kurnalpi Terranes. The symbol  $\mu$  is defined as  $^{238}\text{U}/^{204}\text{Pb}$ , integrated to the present day

At Erayinia in the Eastern Goldfields Superterrane (Fig. 1), the King VMS occurrence is also characterized by high metamorphic grade due to its proximity to large late granitic intrusions (Hollis et al., 2016b). Furthermore, as Au-rich VMS deposits are associated with advanced argillic hydrothermal assemblages (Mercier-Langevin et al., 2011) the recognition of minerals indicative of such systems may lead to the discovery of Au-rich VMS mineralization in the Yilgarn Craton. In greenschist facies rocks, advanced argillic alteration is represented by minerals such as kaolinite, pyrophyllite, andalusite, corundum and topaz (Bonnet and Corriveau, 2007). At granulite facies, metamorphosed advanced argillic assemblages are represented by sillimanite, kyanite and quartz-bearing rocks (Bonnet and Corriveau, 2007).

- A dramatic improvement has been made in geophysical techniques, particularly electromagnetic methods which, when tailored correctly to Australian conditions, can be used to search for massive sulfides in the Yilgarn Craton. It is now known that both the Scuddles and Teutonic Bore deposits have electromagnetic (EM) responses (Yeats, 2007). At Jaguar, a fixed loop transient EM (Crone 'DeepEM') survey across the volcanic stratigraphy identified a strong 1800 m conductor immediately west of the Warramboe gossan (Ellis, 2004). Subsequent drilling delineated the 1.6 Mt Jaguar deposit (at 11.3% Zn, 3.1% Cu, 0.7% Pb and 115 g/t Ag; Jabiru Metals, 2006). Similar techniques are now being routinely applied across the craton, with successes at Wheatley, Narndee, Southern Gossan, Hollandaire, Erayinia/King and Quinns (see following sections).

This report both documents all major VMS occurrences in the Yilgarn Craton identified to date using published literature and publicly available company reports, and presents a petrochemical account of Yilgarn VMS associations using the extensive geochemical dataset of Hollis et al. (2015).

## Regional geology\*

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. 1a). East of the Ida Fault, the Eastern Goldfields Superterrane is subdivided into the Kalgoorlie, Kurnalpi, Burtville and Yamarna Terranes (Pawley et al., 2012; Fig. 1a). Terranes are subdivided into domains, each of which is bounded by an interconnected system of faults (Cassidy et al., 2006).

How the various greenstone belts of the Yilgarn Craton formed and their stratigraphic context remains controversial, with some workers favouring plume

processes and others invoking Archean subduction. That subject is largely beyond the scope of this report but is detailed in Barnes et al. (2012). Here we favour a largely autochthonous model for explaining the geology, geochemistry and distribution of greenstone belts (after Ivanic et al., 2012; Barnes et al., 2012; Barnes and Van Kranendonk, 2014; Mole et al., 2015; Hollis et al., 2015), which does not require long-lived subduction in the Eastern Goldfields Superterrane.

## 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. 1a). The 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., 2014). Both were intruded by felsic magmas (3.3 Ga; e.g. Dugel and Eurada Gneisses) and deformed and metamorphosed to amphibolite and granulite facies prior to the deposition of supracrustal rocks such as those preserved in the Jack Hills greenstone belt (Wyche et al., 2014). Early Archean 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., 2014).

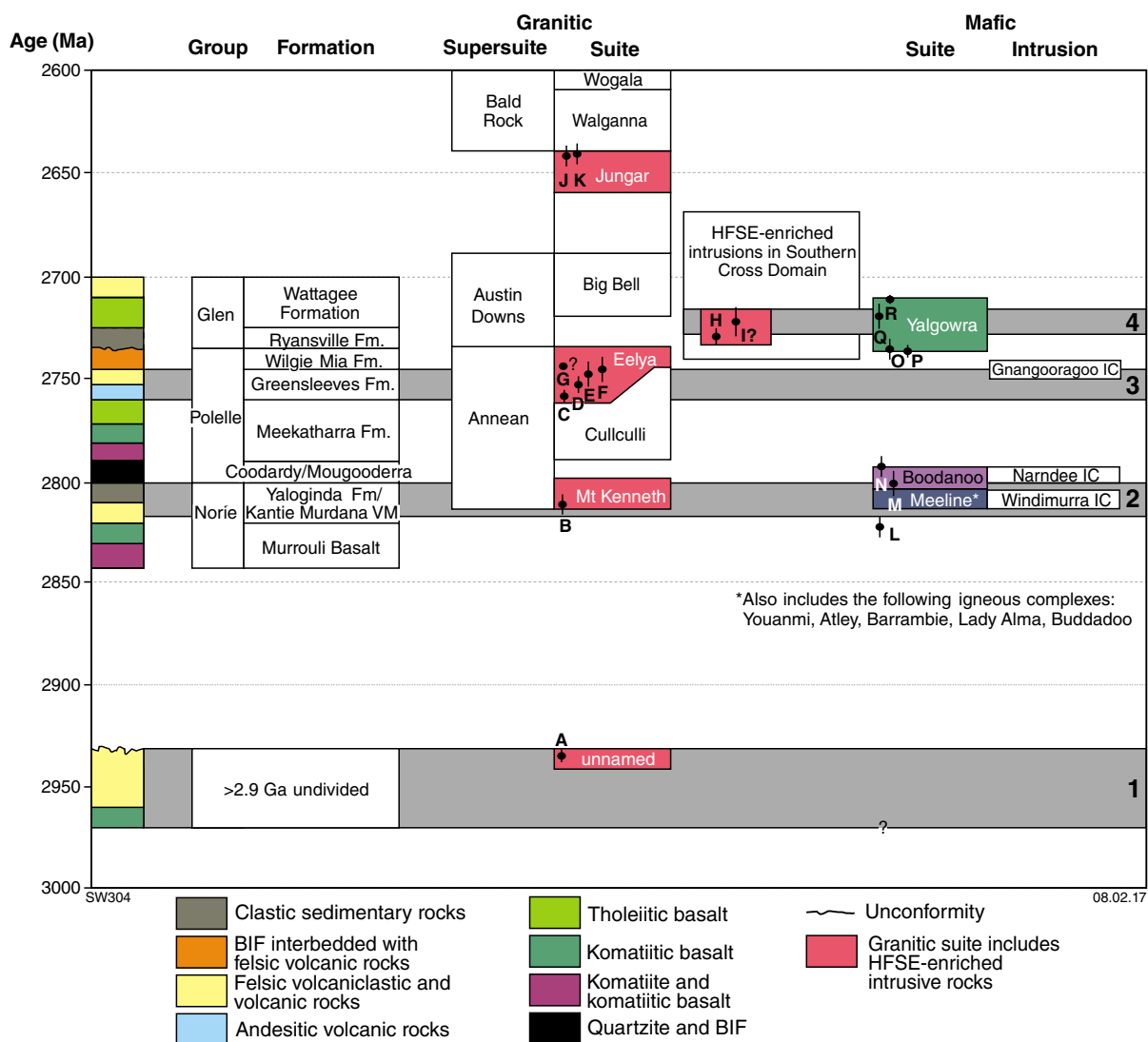
The South West Terrane (Fig. 1a) comprises strongly deformed, high-grade granitic gneiss, and metasedimentary and meta-igneous rocks intruded by 2750–2620 Ma granitic rocks and pegmatites (Mole et al., 2012). Supracrustal successions range in age from 3200–3010 Ma in the Chittering, Jimperding and Balingup(?)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

## Youanmi Terrane

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., 2015). Detrital zircons in quartzites, and xenocrystic zircons from intrusive and extrusive rocks, date back to >4.0 Ga (Wyche, 2007). Van Kranendonk et al. (2013) recently presented a revised stratigraphy for the long-lived, autochthonous Murchison Domain (western Youanmi Terrane; Fig. 3), which is likely comparable to the northern part of the Southern Cross Domain (eastern Youanmi Terrane; Fig. 1a).

Early supracrustal sequences in the Murchison Domain, which formed prior to 2.9 Ga (Fig. 3), are locally preserved in the Yalgoo–Singleton (2.96–2.93 Ga; Wang, 1998), Weld Range (2.97 Ga; Wingate et al., 2008), Tallering (2.94 Ga) and Twin Peaks (3.0 Ga; Pidgeon and Wilde, 1990b) greenstone belts (Fig. 1b). All these greenstone belts contain VMS mineralization. In the Southern Cross Domain, supracrustal sequences of similar age (i.e. >2.9 Ga) occur in the Ravensthorpe (3.0–2.95 Ga;

\* This section is adapted from Hollis et al. (2015).



**Figure 3.** 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 (after Van Kranendonk et al., 2013; Hollis et al., 2015). Granitic suites with HFSE-enriched geochemical characteristics are highlighted. Areas associated with the four main periods of VMS mineralization in the Youanmi Terrane (indicated by grey bars) include: 1 Golden Grove, Ravensthorpe, Twin Peaks, Talling, 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/Jillewarra, Abbots; 4 Gum Creek greenstone belt (The Cup, Bevan, Eds Bore), Wattagee Well(?), Marda Complex(?). A to R represent SHRIMP U–Pb zircon ages for HFSE-enriched granitic rocks (Hollis et al., 2015): A, Mount Gibson monzogranite; B, Courlbarrloo tonalite; C, P biotite granite; D, Eelya granite; E, monzogranite; F, Peter Well Granodiorite; G, Keygo granophyric granodiorite; H, Butcher Bird Monzogranite; I, Montague monzogranite; J, Damperwah granite; K, Coolamen hornblende–biotite granite. SHRIMP U–Pb ages for ultramafic–mafic intrusive rocks (Hollis et al., 2015): L, Gabanintha gabbro; M, Narndee gabbro; N, Murroulli dolerite; O, Fleece Pool Gabbro; P, Kathleen Valley Gabbro; Q, Dalgaranga dolerite; R, Waladah Gabbro



Witt, 1999), Koolyanobbing (3.0 Ga; Angerer et al., 2013), Marda–Diemals (3.0 Ga?; Chen et al., 2003), Forrestania (2.9 Ga?; Perring et al., 1996), Southern Cross (2.93–2.91 Ga?; Mueller and McNaughton, 2000) and Lake Johnston (2.92 to <2.78 Ga; Romano et al., 2014) greenstone belts (Fig. 1b).

Following an extended depositional hiatus of up to 110 Ma across the Youanmi Terrane, the unconformably overlying 2825–2805 Ma Norie Group was deposited (Fig. 3; Van Kranendonk et al., 2013). Exposed predominantly across the northern parts of the Murchison Domain, the Norie Group records a major mantle melting event at 2.82 Ga which resulted in the emplacement of large mafic–ultramafic layered intrusions (Ivanic et al., 2010) and the eruption of the Murrouli Basalt (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; Mole et al., 2015), may have resulted in the partial breakup of the proto Yilgarn Craton, with east–west extension marked by younger Nd-isotope model ages (Fig. 2; Czarnota et al., 2010; Huston et al., 2014). The Murrouli Basalt comprises an approximately four kilometre thick sequence of interbedded Ti-rich, Al-depleted komatiites and komatiitic volcanoclastic rocks overlain by tholeiitic basalts (Van Kranendonk et al., 2013). Conformably overlying rocks of the approximately 500 m thick Yaloginda Formation are dominated by felsic volcanic and volcanoclastic sedimentary rocks and interbedded units of ferruginous shale and/or banded iron-formation (Fig. 3; Van Kranendonk et al., 2013). Felsic volcanic rocks coeval with the Yaloginda Formation, for example the Kantie Murdana Volcanics Member, also overlie the large 2.82 Ga layered intrusions (e.g. Windimurra and Narndee Igneous Complexes).

The 2800–2730 Ma Polelle Group (?dis)conformably overlies the Norie Group and consists of the following formations (Fig. 3): 1) the Coodardy Formation, characterized by a thin (100 m thick) unit of basal quartzite and banded iron-formation; 2) the Meekatharra Formation, which comprises a 2.5 km-thick sequence of tholeiitic basalt, komatiitic basalt, komatiite and thin, interflow 2800–2760 Ma felsic volcanoclastic sedimentary rocks; 3) the Greensleeves Formation, dominated by a ≤5 km thick, 2760–2740 Ma, andesitic to rhyolitic volcanic and volcanoclastic rocks; and 4) and the Wilgie Mia Formation, characterized by interbedded banded iron-formation, shale and felsic volcanoclastic rocks (Van Kranendonk et al., 2013). Subduction affinity magmatism during deposition of 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).

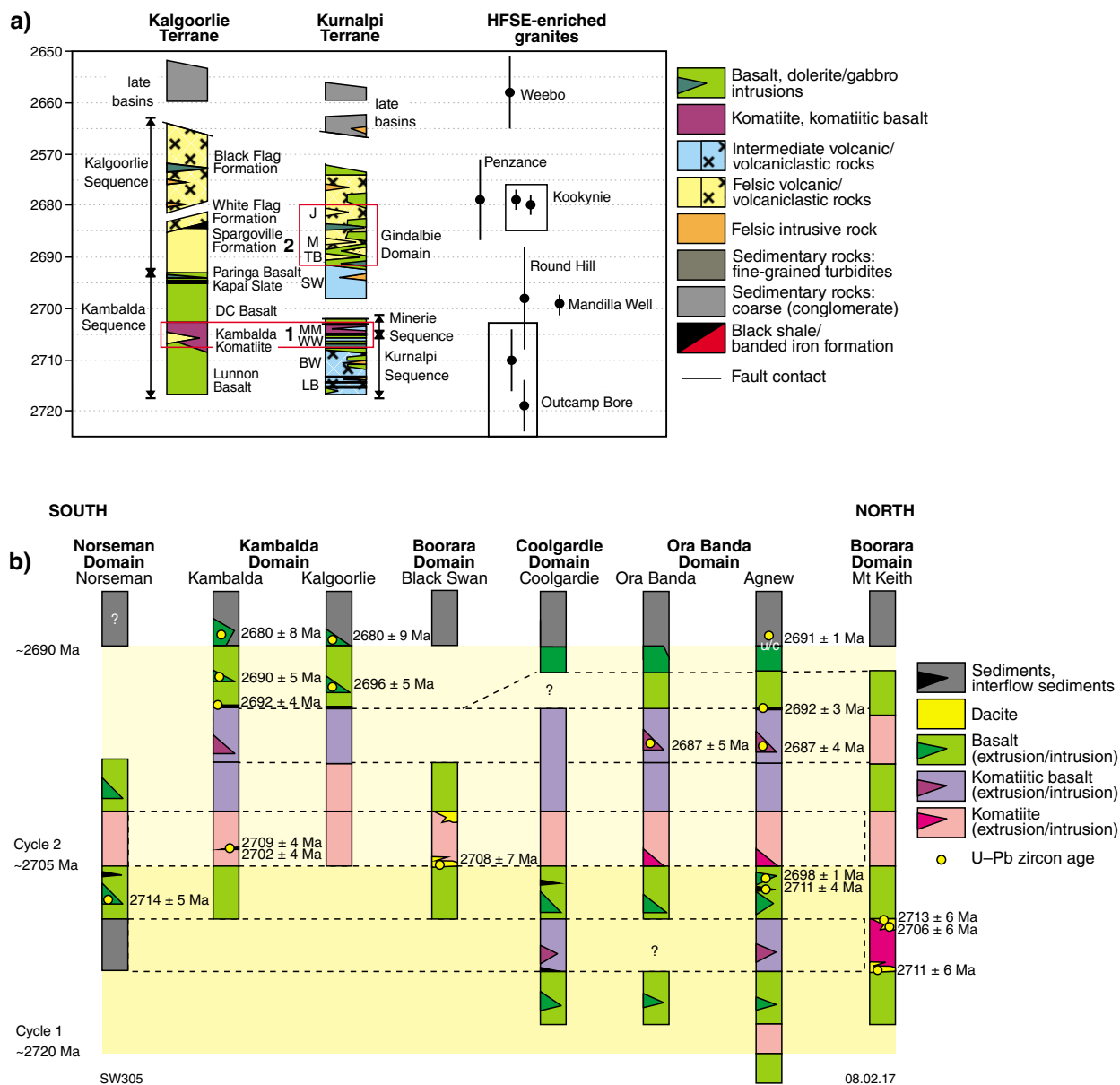
A second (less significant) unconformity separates the Polelle Group from the overlying 2735–2700 Ma Glen Group (Fig. 3), which includes: 1) the Ryansville Formation, dominated by clastic sedimentary rocks; and 2) the Wattagee Formation, characterized by komatiitic basalt and subordinate rhyolite. The deposition of the Wattagee Formation was coeval with the emplacement of widespread, thick and differentiated sills of the Yalgowra Suite (Fig. 3), predominantly hosted in the

older Greensleeves Formation (Ivanic et al., 2010; Wyche et al., 2014), and with komatiitic volcanism in the Eastern Goldfields Superterrane (Fig. 4).

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 in the central part of the Southern Cross Domain (Fig. 1b), a lower greenstone sequence, possibly 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 (Chen et al., 2003). Recent U–Pb zircon geochronology on an intrusive gabbro (c. 2796 Ma; Wingate et al., 2011b) from the lower greenstone sequence suggests it may be equivalent to mafic rocks which intruded the Norie Group at this time (Fig. 3). This implies the Murchison and northern part of the Southern Cross Domains shared a common history prior to 2.8 Ga (Riganti et al., 2010). Ages of assemblages in the Booylgoo Range greenstone belt, similar to the lower greenstone sequence, are unknown (Wyche et al., 2014). Farther north in the Southern Cross Domain, c. 2722 Ma felsic volcanic and volcanoclastic rocks (Bodorkos et al., 2006), clastic sedimentary rocks, and abundant graphitic shale in the Gum Creek greenstone belt (Fig. 1b) host VMS mineralization (e.g. The Cup, Bevan). Granitic rocks, constrained to c. 2800 Ma (Wingate and Bodorkos, 2007a), intrude the northern end of the Gum Creek greenstone belt, indicating an older age for part of the stratigraphy.

## Eastern Goldfields Superterrane

Although local stratigraphy has been established for a number of greenstone belts of the Eastern Goldfields Superterrane, a detailed regional stratigraphy has only been described for the southern part of the Kalgoorlie Terrane (Fig. 4). This consists of a lower 2710–2692 Ma mafic–ultramafic succession (Beresford et al., 2005; ‘Kambalda Sequence’) succeeded by the 2690–2660 Ma ‘Kalgoorlie Sequence’ (Krapež and Hand, 2008). The latter is characterized by a >3 km thick package of volcanoclastic rocks, felsic volcanic rocks, and mafic intrusive complexes with minor mafic volcanic rocks (Squire et al., 2010). The mafic–ultramafic succession is related to a second major plume event in the Yilgarn Craton at 2.72 Ga, broadly contemporaneous with komatiitic magmatism in the Wattagee Formation and the emplacement of the Yalgowra Suite across the Youanmi Terrane (Fig. 3). The occurrence of geochemically similar komatiites and basalts at the same relative stratigraphic position across the Kalgoorlie and Kurnalpi Terranes of the Eastern Goldfields Superterrane between c. 2705 and 2690 Ma (Barnes et al., 2012) suggests the eastern Yilgarn Craton was assembled by c. 2705 Ma and has a common history. Plume-related komatiitic cumulate bodies of the Kalgoorlie Terrane host just over half the entire global Ni endowment within komatiites and ferropicrites (Barnes, 2006; Barnes and Fiorentini, 2012). Between c. 2692 and 2680 Ma in the western Kurnalpi Terrane, volcanic centres were associated with largely bimodal (basalt–rhyolite) volcanic and associated sedimentary rocks, although some contain significant volumes of andesites.



**Figure 4.** Stratigraphic scheme for the Eastern Goldfields Superterrane (after Czarnota et al., 2010). Localities: BW, Bore Well; J, Jeedamya; LB, Liberty Bore; M, Melita; MM, Murrin Murrin (i.e. Anaconda); SW, Spring Well; TB, Teutonic Bore; WW, Welcome Well. SHRIMP U–Pb ages for HFSE-enriched granitic rocks: 1 Nelson (1997b); 2 Dairy Monzogranite: Geoscience Australia sample 96969024 from Zone 51, MGA 35327E 6754664N (DC Champion, Geoscience Australia, written comm., January 2013); 3 Fletcher et al. (2001); 4 Nelson (1997b); 5 Nelson (1996). Two main episodes of VMS mineralization are recognized at 2705–2700 Ma: Anaconda; and 2690–2680 Ma: Teutonic Bore camp, King, Jungle Pool

These rocks have been attributed by some workers as forming in arc–rift environments (Barley et al., 2008) and are broadly contemporaneous with the early Black Flag Group (Fig. 4). Late doming and extension associated with the emplacement of a widespread high-Ca TTG suite produced the late clastic basins of the Yilgarn Craton (Wyche 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 (Fig. 5). 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.

## VMS occurrences in the Yilgarn Craton

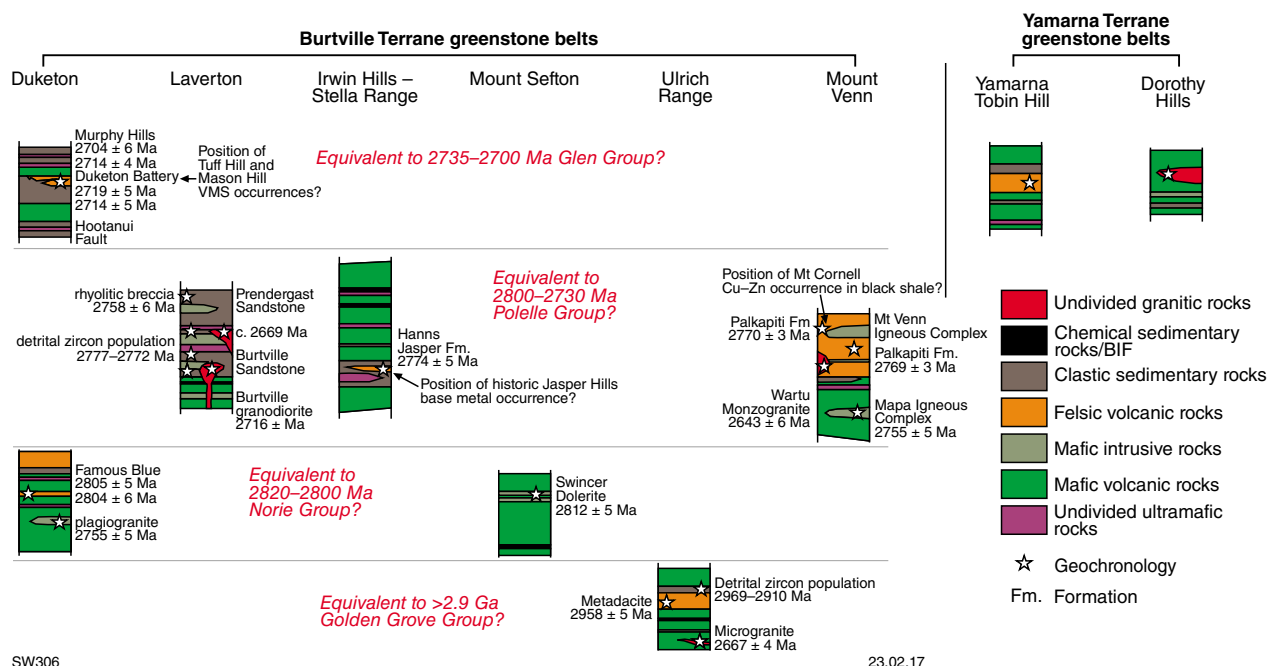
This section summarizes significant VMS finds in the Yilgarn Craton as detailed in published papers, company reports and unpublished theses. Prospect names and locations are from the Western Australian Department of Mines and Petroleum MINEDEX database (GSWA, 2015b).

Economic VMS mineralization in the Yilgarn Craton is largely restricted to two main zones of juvenile crust, as revealed through regional (Nd, Pb, Hf) isotope variations (Ivanic et al., 2012; Huston et al., 2014; Mole et al., 2014, 2015). Interpreted as an Archean paleo-rift zone (see Huston et al., 2014), the Cue Zone of the northern Youanmi Terrane (Fig. 2a) is associated with at least three episodes of VMS mineralization (Fig. 3; and reviewed in Hollis et al., 2015):

1. an initial stage, from c. 2980 to 2930 Ma, in bimodal to dominantly felsic greenstone belts (e.g. Mount Gibson, Golden Grove, Weld Range; Yeats and Groves, 1998; Sharpe and Gemmell, 2002; Guillianse, 2014)
2. at c. 2815 Ma, during eruption of the plume-related Norie Group and coeval with the emplacement of at least five large igneous complexes at shallow levels in the crust (e.g. Austin–Quinns, Youanmi – Just Desserts; Ivanic et al., 2010; Hassan, 2014; Duuring et al., 2016)
3. between c. 2760 and 2745 Ma during the deposition of the Greensleeves Formation (e.g. Hollandaire, Dalgarranga, Mount Mulcahy; Hayman et al., 2015).

An additional VMS event in the northeastern Youanmi Terrane (Fig. 1), at c. 2725 Ma, is restricted to the southeastern Gum Creek greenstone belt (e.g. The Cup, Bevan, Blind Bat; Hollis et al., 2015). This age is coincident with Yalgowra Suite mafic magmatic event (Ivanic et al., 2010) and may be related to further rift development as noted farther west in the Glen Group (Van Kranendonk et al., 2013).

A second, northerly trending paleo-rift zone in the Yilgarn Craton is indicated in the Kurnalpi Terrane in the Eastern Goldfields Superterrane (Fig. 1; Huston et al., 2014). The relationship between this area of juvenile crust and Cu–Zn mineralization is evident in Figure 2, with significant resources mined around Teutonic Bore (Hallberg and Thompson, 1985) and sub-economic VMS mineralization to the northeast (at Tuff Hill, Mason Hill, Fisher Well; Ferguson, 1999) and farther south (e.g. Jungle Pool, Anaconda, Erayinia/King, Nimbus) (Fig. 2; Hollis et al., 2015, 2016b).



**Figure 5. Stratigraphic scheme for greenstone belts in the Burtville and Yamarna Terranes of the northeastern Yilgarn Craton (modified from Pawley et al., 2012)**

## Youanmi Terrane

There has been a significant history of VMS exploration and mining in the Murchison Domain of the Youanmi Terrane, especially in the Yalgoo–Singleton greenstone belt at Golden Grove (e.g. Gossan Hill, Scuddles) and Mount Gibson. In more recent years, significant discoveries have been made across the Youanmi Terrane in areas once considered largely unprospective. Significant occurrences of VMS mineralization identified to date include: 1) new resources at Austin (Quinns), Just Desserts and Hollandaire; 2) the upgrading of Manindi (Freddie Well) deposit; 3) intercepts at Narndee and Mount Mulcahy; 4) the characterization of VMS-associated hydrothermal systems in the Twin Peaks, Barloweerie, and Tallering greenstone belts (see Table 1, Fig. 1a). Near-mine and along-strike exploration at Golden Grove has also significantly increased the resource inventory of this camp. By the end of 2004, the Golden Grove camp contained combined resources and production of about 40.2 Mt at 1.8% Cu, 0.9% Pb, 7.6% Zn, 103 g/t Ag and 0.8 g/t Au (Gawlinski, 2004).

## VMS mineralization prior to 2.9 Ga

### Golden Grove camp (Yalgoo–Singleton greenstone belt)

The Golden Grove VMS camp is located in the Warriedar fold belt of the Yalgoo–Singleton greenstone belt (Murchison Domain; Figs 1b, 6), approximately 225 km east of Geraldton and 475 km north-northeast of Perth (Gawlinski, 2004). The discovery of mineralization at Gossan Hill in 1971 was the first significant VMS deposit identified in the Yilgarn Craton (Frater, 1983). The Gossan Hill deposit consists of two primary copper and zinc resources (7.0 Mt at 3.4% Cu; 2.2 Mt at 11.3% Zn, 102 g/t Ag and 1.5 g/t Au) overlain by weathered copper–gold–silver oxide resources (5.3 Mt at 1.5% Cu; 2.2 Mt at 86 g/t Ag and 2.2 g/t Au; Sharpe and Gemmell, 2001). Following this initial success, a second substantial find northwest of Gossan Hill was identified at Scuddles in 1979 (pre-mining reserves of 15.9 Mt at 2.6% Cu, 1.5% Zn, 0.2% Pb, 21 g/t Ag, 0.6 g/t Au; see following). Both deposits occur in the Golden Grove Formation, which has a strike length of approximately 36 km (Fig. 6; Gawlinski, 2004).

The Warriedar fold belt (Baxter, 1991) contains tholeiitic basalt, banded iron-formation, and felsic volcanic and sedimentary rocks, which have been metamorphosed to greenschist facies assemblages (Watkins and Hickman, 1990; Clifford, 1992). Locally, the stratigraphy is characterized by a thick package of felsic and intermediate volcanic, volcanoclastic and sedimentary rocks that dip steeply southwest (Gawlinski, 2004). SHRIMP U–Pb zircon geochronology from Golden Grove has constrained the age of the host sequence to 2960–2930 Ma (Pidgeon and Wilde, 1990b; Wang, 1998; Wingate et al., 2015a,b,c). The stratigraphy of the Golden Grove area used in this Report (Fig. 7) follows Clifford (1992) who named three

groups\*: Gossan Hill (lower), Thundelarra, and Minjar (upper). The Gossan Hill Group of Clifford (1992) is informally divided into the Shadow Well, Gossan Valley, Golden Grove, Scuddles, and Cattle Well formations (Fig. 7). Localized rift-related activity is well recognized. VMS mineralization predominantly occurs in laminated sedimentary successions of the Golden Grove formation (units GG2, GG4, GG6), with lesser zinc and lead mineralization in the overlying Scuddles formation (Fig. 7; Gawlinski, 2004).

The Golden Grove formation is characterized by the products of distal explosive felsic volcanism, redeposited by successive mass flow processes (Sharpe and Gemmell, 2001). It includes pumiceous breccias, sandstones, siltstones, chert horizons and minor felsic lavas (Gawlinski, 2004). Six members have been identified (Fig. 7) and the absence of members GG2 and GG3 at Gossan Hill has been suggested to reflect a local depositional hiatus caused by uplift along syndepositional structures (Sharpe and Gemmell, 2001). Lithofacies can vary significantly within and between members (e.g. from pebble breccias to sandstone to siltstone; Sharpe and Gemmell, 2001). The upper parts of the formation reflect a waning of sediment influx, with unit GG6 representing ambient background sedimentation (Sharpe and Gemmell, 2002).

The Scuddles formation, which directly overlies VMS mineralization at Golden Grove and Scuddles near the top of GG6, consists of quartz- and feldspar-phyric rhyodacite, which is overlain and intruded by feldspar- and quartz-phyric dacite. Dacite also intrudes members GG4 to GG6 of the underlying Golden Grove formation and is interpreted to be an intrusive–extrusive dacite dome that overlies its discordant volcanic feeder (Sharpe and Gemmell, 2001). Therefore, the contact between unit GG6 and the Scuddles formation records the onset of proximal felsic volcanism in the area and further geodynamic change in the basin's evolution. The position of original synvolcanogenic structures at the Golden Grove VMS deposit are highlighted by the: 1) asymmetry of massive sulfides (both ore zones), massive magnetite and stringer zones relative to the volcanic feeder for the Scuddles formation dacite; 2) a decreasing thickness of massive sulfide, magnetite and stockwork from discordant contact of the hangingwall dacite; 3) the widest variation in  $\delta^{34}\text{S}$  values at the southern end of the Gossan Hill orebody away from central feeder (Sharpe and Gemmell, 2000).

### Gossan Hill mineralization

There are two stratigraphically separate ore zones in the Gossan Hill VMS deposit, both of which are largely stratabound and are interconnected by sulfide veins along the southern margin of the Scuddles formation hangingwall dacite (Fig. 7). Unit GG4, characterized by quartz-rich, tuffaceous, bedded sandstone, siltstone and granule to pebble breccias, hosts significant magnetite mineralization and copper-rich massive and vein sulfides.

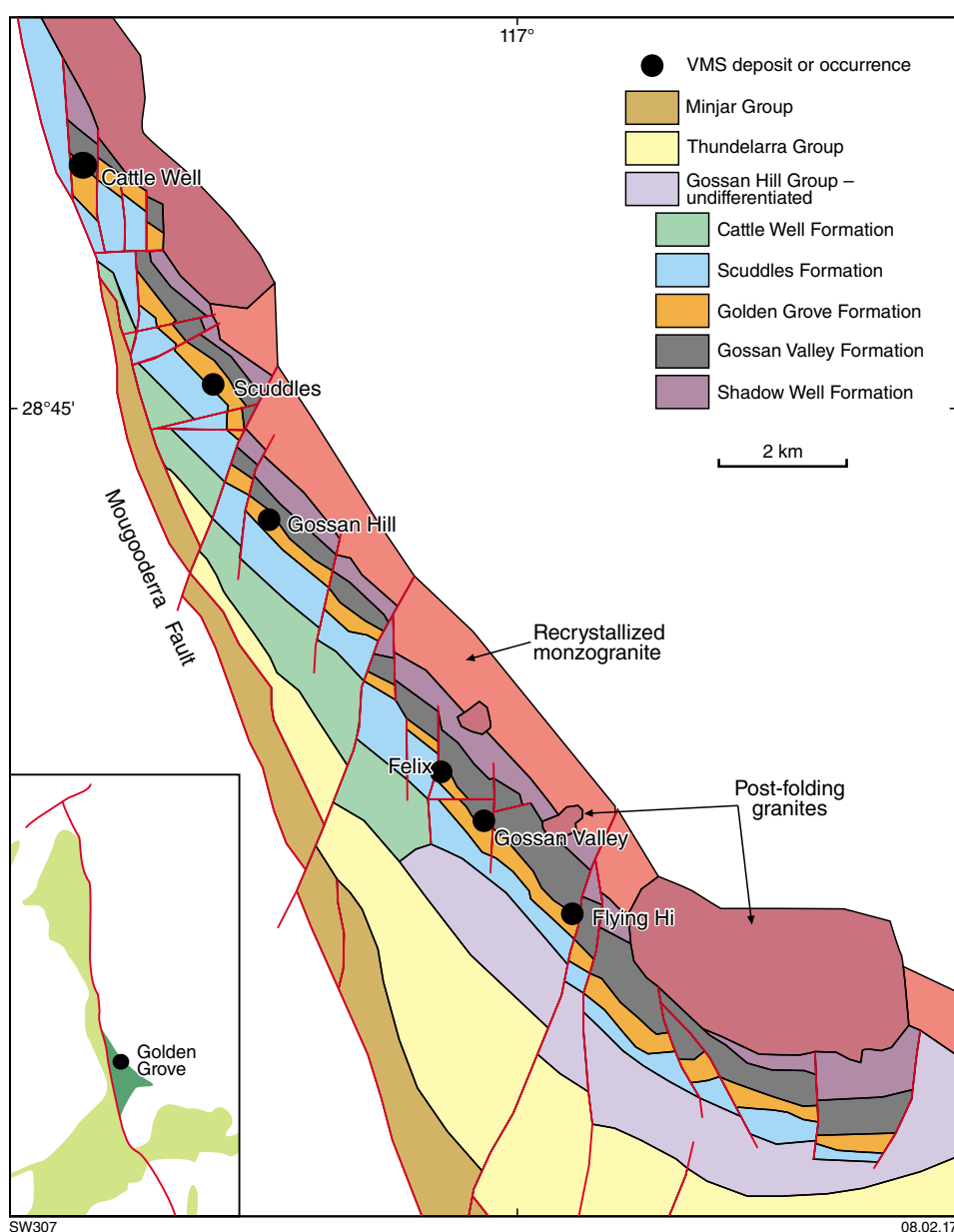
\* This stratigraphy is being revised by GSWA and the new interpretations may be viewed as they become available using the ENS Lithstrat Unit Search Tool in GeoVIEW.WA <[dmp.wa.gov.au/ens](http://dmp.wa.gov.au/ens)>.



This is referred to as the lower ore zone (7 Mt at 3.4% Cu) and varies from podiform massive pyrite–chalcopyrite–pyrrhotite–magnetite to sheet-like massive magnetite–carbonate–chlorite–talc assemblages (Sharpe and Gemmell, 2001). Unit GG6 is characterized by bedded siltstone, sandstone and polymict pebble breccias, and hosts zinc-rich massive and vein sulfide as the upper ore zone (2.2 Mt at 11.3% Zn, 1.5 g/t Au, 102 g/t Ag). This ore zone contains stratabound massive sphalerite–pyrite–chalcopyrite that overlies discordant, mound-like massive pyrite–pyrrhotite–chalcopyrite–magnetite (Sharpe and Gemmell, 2001). Low lead, an absence of sulfate minerals, and common pyrrhotite in the deposit are consistent with Archean VMS deposits in general. The principal sulfides of the Gossan Hill orebodies include sphalerite, pyrite, chalcopyrite, pyrrhotite and galena. Sphalerite,

tetrahedrite, cobaltite, arsenopyrite, bornite, cassiterite, electrum and native silver only occur in the upper zone (Sharpe and Gemmell, 2001). Pyrrhotite is more abundant in the lower zone, but present in both.

Alteration assemblages associated with massive sulfides are dominated by quartz, chlorite, magnetite and ankerite–siderite. A quartz alteration envelope surrounds the upper ore zone and stockwork, and a chlorite and ankerite–siderite alteration envelope surrounds the lower sulfide zone (Sharpe and Gemmell, 2001). Gradational upper and lower contacts of massive sulfides to bedded strata of the upper orebody, and common patches of sulfide-veined beds within massive sulfides, indicate the upper zone formed through replacement processes (Sharpe and Gemmell, 2001). Broad, diffuse, stratiform zones of footwall alteration (quartz–chlorite–sericite–carbonate–



**Figure 6.** Detailed geology of the Golden Grove area of the central Yalgoo–Singleton greenstone belt (modified from Sharpe and Gemmell, 2002). For regional setting, see Figure 1b

sulfide) under the Gossan Hill and Scuddles mineralization (300 m thick by 10 km long; Barley, 1992) is also consistent with the replacement origin of these orebodies, with hydrothermal flow along porous volcanoclastic and sedimentary strata. Localized hydrothermal systems developed at sites of synvolcanic faults are represented by copper-rich stockwork zones without extensive discordant alteration pipes. Minor effusive activity also occurred at Gossan Hill during the deposition of GG6, represented by hydrothermal chert–sulfide layers within and adjacent to the upper zinc-rich ore zone (Sharpe and Gemmell, 2001).

A large tonnage of magnetite (about 12 Mt) is also associated with the copper-rich parts of the deposit in GG4. The presence of magnetite is common in the Superior Province of Canada but is atypical of Australian polymetallic VMS deposits (Sharpe and Gemmell, 2001). Gradational and interfingering contacts between volcanoclastic units and magnetite support the formation of massive magnetite by subseafloor replacement processes from high-temperature (>300 °C), slightly acidic, low- $fO_2$ ,  $H_2S$ -poor hydrothermal fluids (Sharpe and Gemmell,

2001). In the lower orebody, two podiform discontinuous zones of massive pyrite occur within the basal 40 m of GG4, and these interfinger with sulfide stringer and massive magnetite (Sharpe and Gemmell, 2001).

The Gossan Hill deposit also shows a broad metal zonation from a copper–iron ( $\pm$  gold) rich lower ore zone in unit GG4, upwards through copper–zinc–iron in the upper ore zone of GG6, passing upwards and laterally to high grade zinc–lead–silver–gold ( $\pm$  copper) at the top. Sulfur isotopes (see Sharpe and Gemmell, 2001) similarly show a broad systematic increase in  $\delta^{34}S$  of about 1.2‰ from the base to the top of deposit. The copper-rich lower ore zone was suggested to have formed from a relatively uniform, reduced-sulfur source dominated by leached igneous rock sulfur with minor magmatic input, whereas the upper zinc-rich ore zone formed by mixing of hydrothermal fluid containing leached igneous sulfur with Archean seawater (Sharpe and Gemmell, 2001). Further detail on geology and mineralization of the Gossan Hill deposit is given in Frater (1983) and subsequent papers by Sharpe and Gemmell (2000, 2001, 2002).

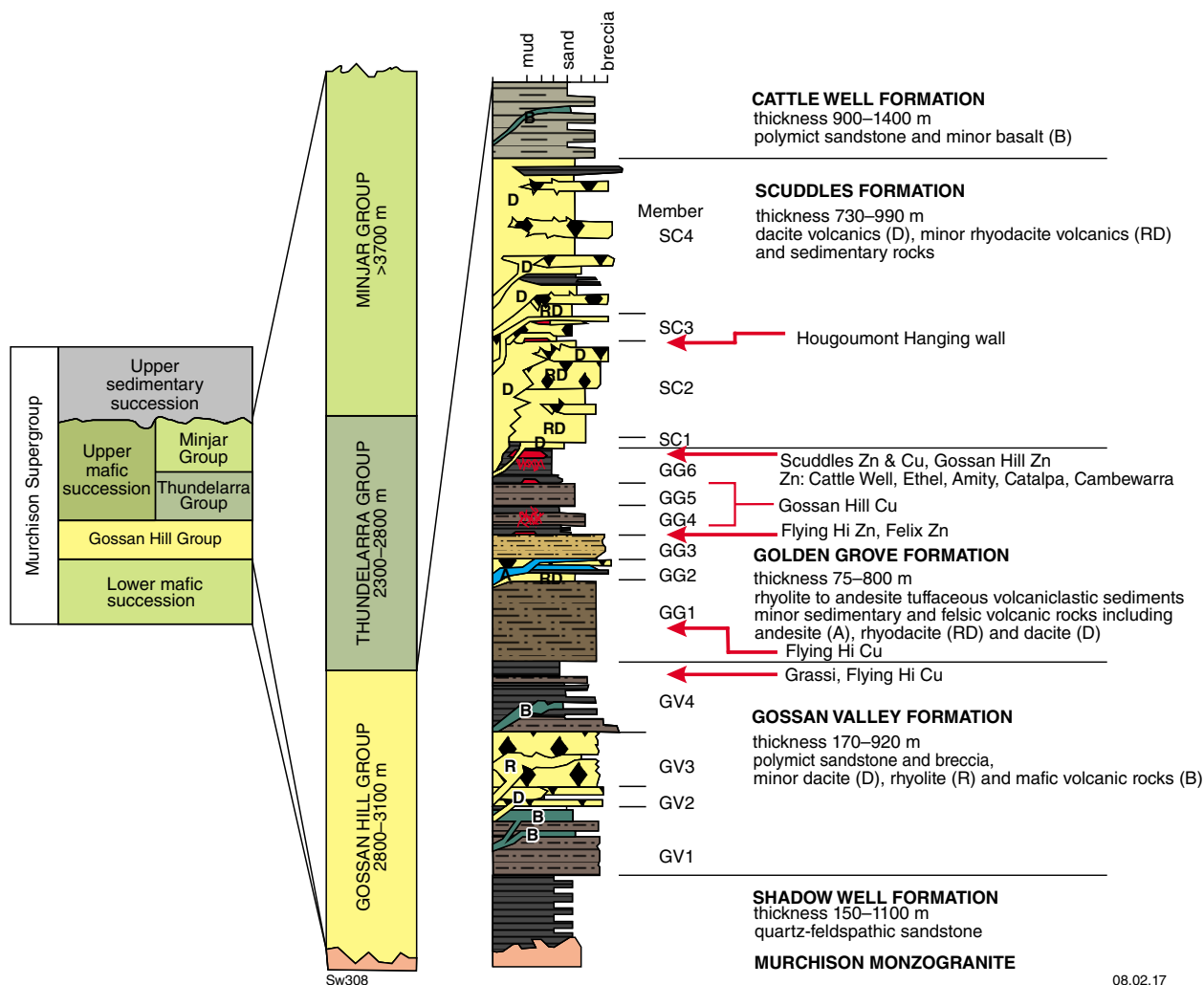


Figure 7. Stratigraphy of the Golden Grove area in the central Yalgoo–Singleton greenstone belt. A, Andesite; B, basalt; D, dacite; R, rhyolite; RD, rhyodacite. Massive sulfides and stringer mineralization in red (modified from Sharpe and Gemmell, 2002)

### Scuddles mineralization

Following the discovery of the Gossan Hill VMS deposit by Aztec Exploration in 1971, together with their joint venture partners (Amax Exploration, and later EZ Exploration), Aztec searched the surrounding area for additional mineralization between 1971 and 1978 (Boyd and Frankcombe, 1994). After Esso Exploration and Production Australia Inc. were brought into the joint venture, massive sulfide mineralization was intercepted at depth in 1979 (25.5% Zn, 2.4% Pb, 0.49% Cu, 221 g/t Ag, 1.14 g/t Au over true width of 6 m) through an integrated exploration programme utilizing an aeromagnetic survey, gradient array IP (induced polarization), RAB (rotary air blast) drilling, detailed mapping, diamond drilling, and a pulse electromagnetic survey (see Robinson and Belford, 1991).

VMS mineralization at Scuddles (pre-mining reserves of 15.9 Mt at 2.6% Cu, 1.5% Zn, 0.2% Pb, 21 g/t Ag, 0.6 g/t Au) is at the same stratigraphic horizon as the upper ore zone at Gossan Hill (top of GG6) with stringer sulfides extending down to the base of unit GG5 (Sharpe and Gemmell, 2001). No mineralization in unit GG4 equivalent to the lower orebody at Gossan Hill has been identified. Mineralization occurs as two main massive sulfide lenses with a zone of stockwork zinc mineralization to the north (Barley, 1992) and has been described by Ashley et al. (1988) and Mill et al. (1990). Three types of massive sulfide can be recognized: 1) massive sphalerite (>50% sphalerite) at the top of the deposit; 2) massive pyrite (<50% sphalerite, <5% chalcopyrite), which interfingers with zone 1; and 3) copper-rich massive pyrite (>5% chalcopyrite) near the base of the deposit (Barley, 1992). Consequently, as at Gossan Hill, the Scuddles deposits exhibits a classic VMS metal zonation from a footwall stringer copper zone, upwards into copper-rich, iron-rich and then zinc-rich mineralization (Boyd and Frankcombe, 1994). Massive sulfides are composed predominantly of pyrite and sphalerite, with variable pyrrhotite, chalcopyrite, magnetite, galena, tetrahedrite, arsenopyrite, electrum and silver minerals (Ashley et al., 1988; Mill et al., 1990; Whitford and Ashley, 1992). Massive sulfides are underlain by a copper-rich stockwork zone (dominated by pyrite–chalcopyrite) associated with iron-rich chlorite (Guilliamse, 2014). This zone varies with depth from >80% sulfides to <10% sulfides (Barley, 1992). No massive magnetite mineralization has been identified, as at Gossan Hill (Barley, 1992). Peripheral alteration at Scuddles is characterized by albite–chlorite–carbonate–sericite, replaced by a VMS-proximal or footwall quartz–chlorite–sericite  $\pm$  carbonate  $\pm$  sulfide alteration. The mineralized horizon is characterized by chlorite–quartz  $\pm$  talc  $\pm$  sulfides  $\pm$  carbonate  $\pm$  sericite (Whitford and Ashley, 1992).

### Recent developments

Since the initial successes at Gossan Hill and Scuddles, near-mine drilling between 1999 and 2003 resulted in the discovery of several new lenses of VMS mineralization, as summarized in Table 1 and shown in Figure 8. These discoveries, to about 1300 m depth, highlight the potential for further resources at localities across the Yilgarn Craton by drilling to depth. By 2004, 40.2 Mt of VMS mineralization had been delineated in the Golden

Grove camp (at 7.6% Zn, 1.7% Cu, 0.9% Pb, 0.8 g/t Au and 103 g/t Ag; McConachy et al., 2004). In 2015, total reserves at Golden Grove included 8.4 Mt at 0.5% Cu, 12.3% Zn, 1% Pb, 72 g/t Ag and 1.1 g/t Au, and 16.7 Mt at 3.1% Cu, 1.6% Zn, 0.2% Pb, 29 g/t Ag and 0.7 g/t Au (MMG, 2015).

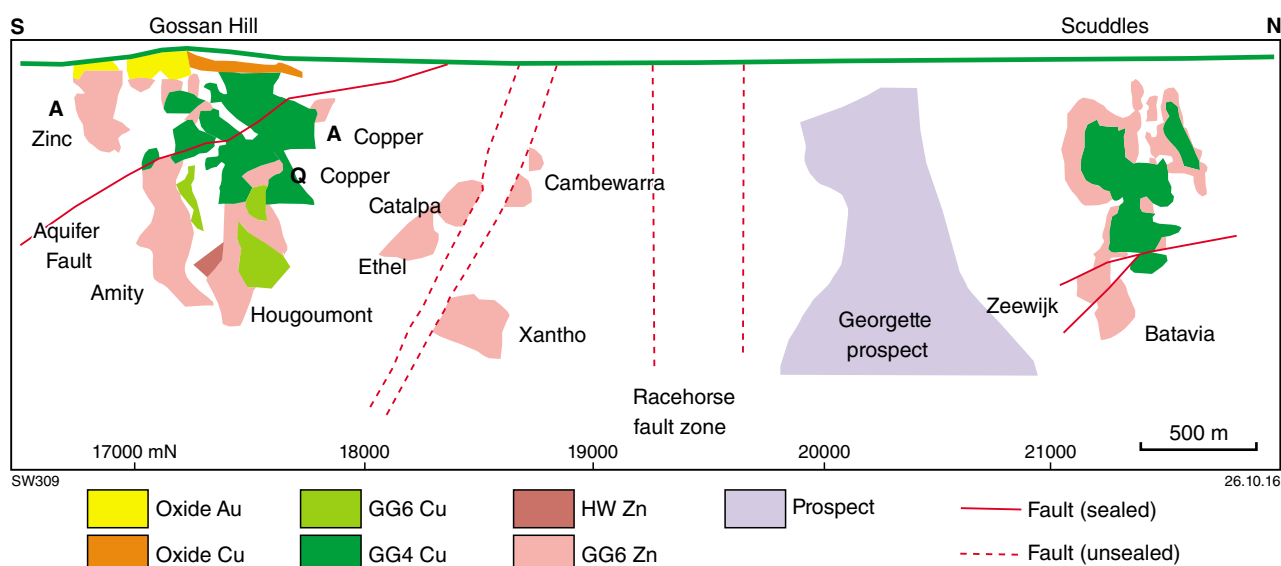
### Mount Gibson (southern Yalgoo–Singleton greenstone belt)

The Mount Gibson base metal-rich gold deposit is hosted within the Mount Gibson shear zone, approximately 120 km southwest of Golden Grove in the southernmost portion of the Yalgoo–Singleton greenstone belt (Fig. 1b; McConachy et al., 2004). Although it was originally gossanous copper–lead–zinc mineralization that attracted major explorers to the area in 1975 (McConachy et al., 2004), gold mineralization soon became the primary focus. By 1984, a lateritic gold resource was outlined (5.3 Mt at 1.6 g/t Au; Yeats and Groves, 1998), with subsequent mining revealing a number of base metal-rich zones characterized by sphalerite and galena (McConachy et al., 2004). Both Gee (1990) and Watkins and Hickman (1990) noted the unusual relationship between gold and copper–lead–zinc mineralization for lode gold mineralization.

Yeats et al. (1996) subsequently demonstrated that the deposit shows evidence for both early VMS-style base metal mineralization at c. 2930 Ma overprinted by later synorogenic shear zone-hosted lode gold mineralization at c. 2630 Ma. Recrystallized and metamorphosed sphalerite–galena–pyrite–pyrrhotite–chalcopyrite–tetrahedrite mineralization is associated with a garnet (spessartine–almandine)–gahnite-bearing schist which immediately overlies gold-bearing quartz–cordierite–muscovite schist (Yeats and Groves, 1998). Geochemical analysis revealed a tholeiitic mafic protolith to both units suggesting the observed mineral assemblages are the products of a metamorphosed hydrothermal system.

Tourmaline chemistry across the deposit is also consistent with a VMS system, whereby Mg-rich compositions are associated with sulfide-rich schists and Fe-rich tourmalines in the sulfide-poor schists (Jiang et al., 2002). Ore schists are characterized by prominent positive Eu anomalies (Jiang et al., 2002) consistent with many active seafloor hydrothermal systems (e.g. Mid-Atlantic Ridge, Manus Basin, Lau Basin, East Pacific Rise; Bau and Dulski, 1999; Douville et al., 1999; Craddock et al., 2010) and sulfide-proximal chemical sediments associated with ancient VMS deposits (e.g. Peter and Goodfellow, 2003).

Although the footwall succession to the Mount Gibson deposit is dominated by tholeiitic mafic rocks (and includes Mg-rich metabasalts with komatiitic components), mineralization occurs in the ‘mixed mine sequence’ (Yeats et al., 1996), where quartz–feldspar porphyries first appear in the stratigraphy. Although these felsic rocks rarely host any mineralization, their sudden appearance suggests the ‘mixed mine sequence’ records a geodynamic shift in the evolution of the basin. Overlying hangingwall units include quartz andesites, minor interflow sedimentary rocks and a thick, monotonous succession of quartz-phyric felsic metavolcanic rocks.



**Figure 8.** Longitudinal section of the Golden Grove VMS camp showing discoveries up to 2004 (modified from Gawlinski, 2004; Yeats, 2007). Near-mine drilling between early 2000 and 2004 added approximately 8 Mt to the resource inventory (Gawlinski, 2004)

The deposit shows a strong base metal zonation from the gold–copper main ore zone to overlying stratiform lead–zinc–silver(–manganese). By the end of September 1994, the Mount Gibson gold project had produced about 17 t of fine gold and in excess of 10 t of silver. Although fewer than 20% of the drill samples were assayed for base metals, some significant intersections have been reported (e.g. 4 m at 13.4% Zn, 0.2% Cu, 0.03% Pb, 0.3 g/t Au and 8 g/t Ag; McConachy et al., 2004).

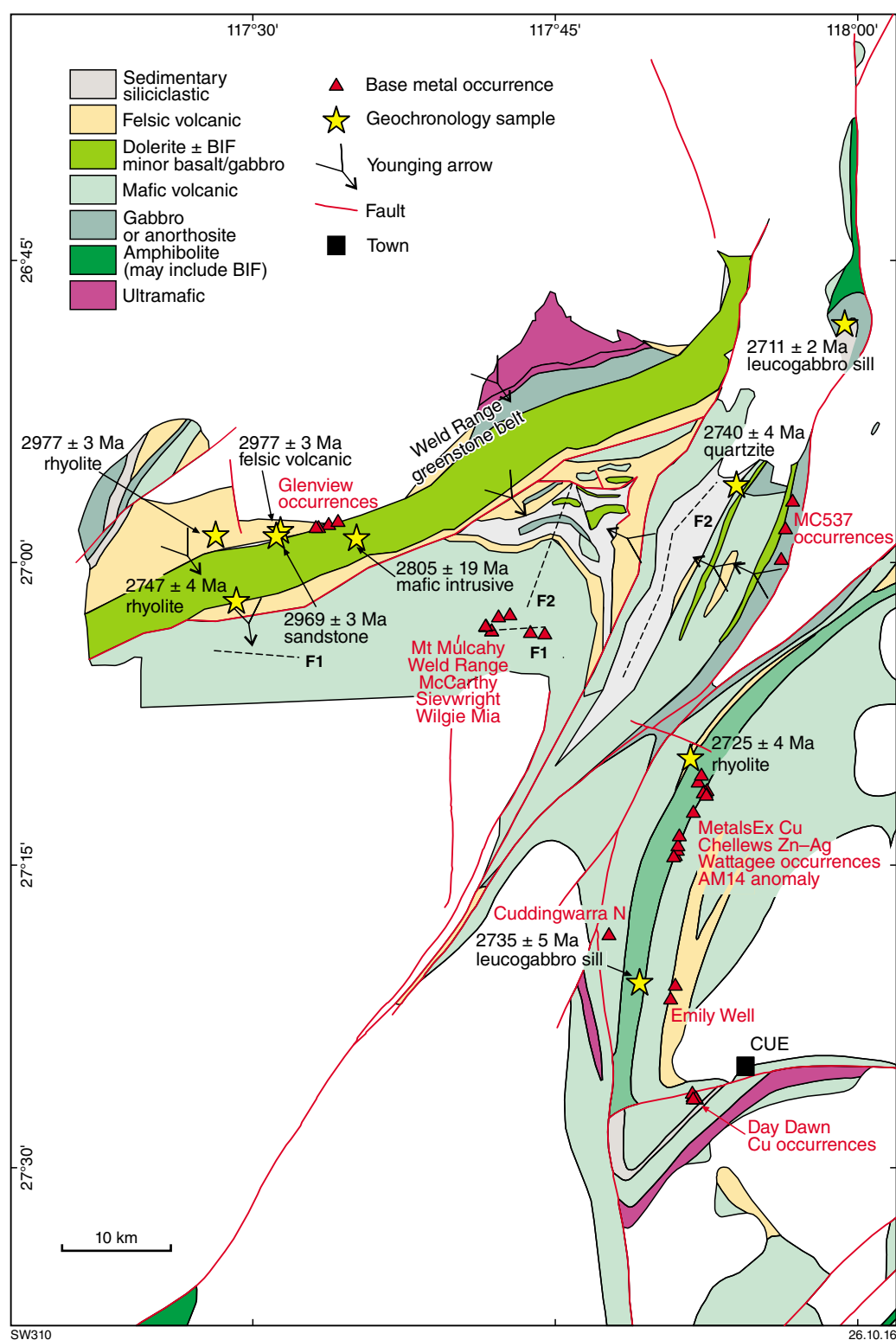
### Weld Range greenstone belt

The Weld Range greenstone belt of the northern Murchison Domain is a northeast-trending (and southward dipping) succession of ultramafic to felsic volcanic rocks, volcanoclastic rocks, and clastic and chemical sedimentary rocks (e.g. banded iron-formation, white-grey chert), intruded by dolerite and gabbro sills (Fig. 9; Watkins and Hickman, 1990; Van Kranendonk et al., 2013; Guiliamse, 2014). Banded iron-formations have been divided into three subdivisions (Madoonga, Lulworth and Wilgie Mia) which host significant iron mineralization (see Duuring and Hagemann, 2013 and references therein). Supracrustal rocks are metamorphosed to lower greenschist facies ( $300 \pm 50^\circ\text{C}$ ,  $<2$  to 3 kbars; Gole 1980). Following the suggested correlation between the Weld Range felsic rocks and those at Golden Grove (Watkins and Hickman, 1990), the area was actively targeted for VMS mineralization in the early 1990s (see Martin et al., 1997; Guiliamse, 2014). The discovery of gossans at Glenview led to the intersection of VMS-style base metal stringer mineralization in a number of holes (e.g. 2 m at 1.47% Pb and 5.73% Zn, and 2 m at 1.5% Cu; Martin et al., 1997), although only minor massive sulfides have so far been discovered (Guiliamse, 2014). A detailed study by Guiliamse (2014) on the prospectivity of the Glenview area shows that many

of the intersected veins are associated with chert and jasper beds within finely laminated volcanoclastic rocks. Mineralization occurs predominantly as pyrite veins with minor occurrences of chalcopyrite, sphalerite and galena. Zinc-rich mineralization has also been intersected in a number of holes. Quartz and chlorite alteration occurs proximal to mineralization.

Several dates have been published for the Weld Range greenstone belt leading to various opinions concerning its age range (ages shown on Fig. 9). SHRIMP U–Pb zircon dating by Wang (1998) yielded an age of  $2752 \pm 9$  Ma for felsic crystal tuff collected from within the banded iron-formations that make up the Weld Range, with older components dated at  $2920 \pm 13$  and  $3263 \pm 9$  Ma. By contrast, Pb–Pb dating by CSIRO yielded ages between c. 3200 and 3162 Ma from galena hosted within hyaloclastic rhyolites (Martin et al., 1997). More recently, U–Pb zircon dating by GSWA has yielded ages of  $>2960$  Ma from the north side of the Weld Range ( $2969 \pm 3$  Ma, GSWA 184112, Wingate et al., 2008;  $2979 \pm 3$  Ma, GSWA 193972, Wingate et al., 2012b). To try and resolve these issues, two samples from the Weld Range stratigraphy were recently dated by GSWA (Guiliamse, 2014). Zircon from a felsic volcanic rock from near the Glenview prospect on the north side of the range yielded an age of  $2977 \pm 3$  Ma, whereas a rhyolite from south of the range yielded a date of  $2747 \pm 4$  Ma. Guiliamse (2014) suggested the felsic VMS-hosting succession at Glenview is of similar age to Golden Grove (i.e.  $>2.9$  Ga) and that a significant unconformity most likely exists in the area. Although the Wang (1998) site has not been relocated, GSWA geochronology from a very fine-grained, bedded, probably tuffaceous outcrop near its stated position has yielded a zircon date of c. 2792 Ma (GSWA 155568, Wingate et al., 2013), suggesting an unconformity between the northern and southern banded iron-formation units.





**Figure 9.** Geology and mineral occurrences in the Weld Range greenstone belt and Mt Mulcahy – Emily Well region of the northern Murchison Domain. Geology is based on GSWA (2014a); mineral occurrences are from GSWA (2015b); geochronology is from GSWA (2015a)

### **Ravensthorpe greenstone belt**

The 3000–2950 Ma Ravensthorpe greenstone belt lies at the southern margin of the Yilgarn Craton (southwest corner of the Southern Cross Domain). Historically, nearly half the State production of copper ore and concentrates has come from the Ravensthorpe greenstone belt (20 115 t of contained Cu; Marston, 1979). Three fault-bound tectonic units are preserved in the Ravensthorpe greenstone belt: the Ravensthorpe ‘Terrane’ (Manyutup Tonalite and Annabelle Volcanics), Carlingup ‘Terrane’, and Cocanarup greenstones (Fig. 10; Witt, 1999). For consistency with the Cassidy et al. (2006) terrane scheme, they are referred to here as assemblages.

The Annabelle Volcanics are dominated by volcanoclastic rocks with less abundant lava flows (basalt to minor rhyolite, dominantly andesitic) and minor dolerite (Witt, 1999). Together with the Manyutup Tonalite, they comprise a calc-alkaline intrusive–extrusive assemblage which has yielded U–Pb zircon ages of 3000–2950 Ma (Savage et al., 1995). These include: 1) a sample of volcanic rock from Kundip (Annabelle Volcanics) at  $2989 \pm 11$  Ma; 2) coarse-grained tonalite at  $2965 \pm 12$  Ma; and 3) a tonalite porphyry dyke at  $2989 \pm 7$  Ma (M Barley, written communication in Witt, 1999). The Carlingup assemblage, exposed east of the Chidnup Fault (Fig. 10) is characterized by mafic to ultramafic volcanic rocks and psammitic to pelitic sedimentary rocks, chert and banded iron-formation (Witt 1999). Minor felsic volcanic rocks are also preserved, and these have yielded a U–Pb zircon age of  $2958 \pm 4$  Ma (GSWA 112163, Nelson, 1995b). The Cocanarup assemblage is characterized by amphibolite-grade pelitic and psammitic metasedimentary rocks, with lesser mafic and ultramafic rocks. No age data are available from these rocks.

Base metal mineralization in the Ravensthorpe greenstone belt is primarily hosted in the Annabelle Volcanics, within about two kilometres of the contact with the coeval Manyutup Tonalite (Marston, 1979), as synvolcanic copper–gold and copper–zinc mineralization (Witt, 1999). Four main centres of mineralization are recognized in the eastern Annabelle Volcanics (see Fig. 10): Mount Cattlin (Ravensthorpe), Mount McMahon, Mount Desmond, Kundip. Synvolcanic mineralization has also been recognized in the western Annabelle Volcanics (Fig. 10) at West River in the southwestern part of the greenstone belt, and in the Carlingup assemblage (e.g. Hecla and Mount Garrity areas). Marston (1979) presented an extensive review on exploration activity, mine production, mineralization styles and alteration. Three main economic mineral associations were noted in the greenstone belt (Marston, 1979): 1) chalcopyrite–gold–pyrite–pyrrhotite–magnetite–ilmenite–quartz; 2) quartz–gold with secondary copper minerals; and 3) chalcopyrite–sphalerite–pyrite–pyrrhotite–quartz. The first association is the most common. Synvolcanic copper–gold deposits occur as discontinuous sheared lenses up to 700 m long, but more commonly <200 m long and 30 m wide. Intense chlorite alteration occurs in andesitic wallrocks (Marston, 1979). At higher metamorphic grades, alteration types associated with synvolcanic copper–gold lodes include: quartz–chlorite(–biotite) veinlets (Kundip to Mount Desmond),

amphibole veinlets (Mount McMahon to Ravensthorpe), garnet- and cordierite-bearing lenses (north and northeast of Ravensthorpe), and a cordierite–orthoamphibole rock which replaces a felsic precursor in the western part of the greenstone belt (Witt, 1999).

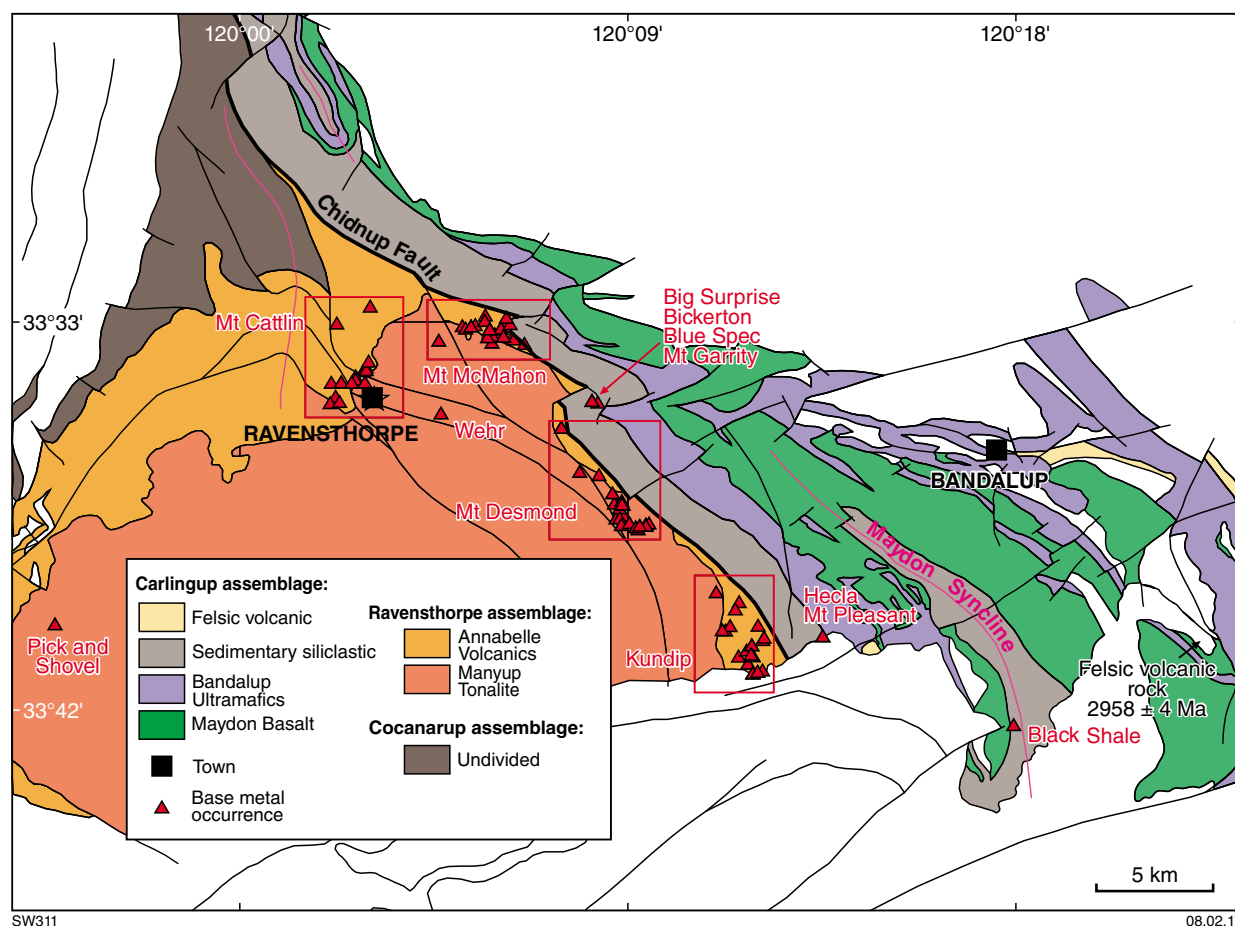
Synvolcanic copper–gold deposits in the Ravensthorpe greenstone belt are characterized by up to about 10% disseminated sulfides. Quartz veins commonly form a minor component. Importantly, most pyrite from these deposits is Co rich, typical of a volcanogenic origin (Marston, 1979). At Kundip, massive and banded sulfide ore is characterized by pyrite–chalcopyrite–magnetite (–gold–pyrrhotite–ilmenite) (Witt, 1999). Minor cobaltite and sphalerite are present in some deposits, with silver primarily as tetrahedrite (Witt, 1999). Zinc-bearing sulfides are relatively rare and occur primarily at West River in the southwestern part of the greenstone belt with few reported examples elsewhere (Marston, 1979). Drilling at Mount Short (far north of Ravensthorpe greenstone belt) has also intersected significant zinc (e.g. 5 m at 2.38% Zn, 0.66% Pb) within a 50 m wide zone of lower grade mineralization (Traka Resources Ltd, 2016). Mass balance calculations on the host sequences of both the copper–gold and copper–zinc deposits of the Ravensthorpe greenstone belt give results typical of VMS systems with gains in FeO, MgO, SiO<sub>2</sub>, and S, and depletions in CaO and Na<sub>2</sub>O in the mineralized zones (see Witt, 1999).

### **Tallering greenstone belt**

In the Tallering greenstone belt (Fig. 1b), approximately 200 km east of Geraldton (western Murchison Domain), hydrothermal alteration characteristic of VMS systems has been discovered at Conquistador, A Zone, and Kerbar (Zenith Minerals Ltd, 2011). The latter locality is associated with copper- and zinc-anomalous gossans in a felsic-dominated volcanic succession. Strong pyrite–sericite alteration associated with anomalous copper and zinc has been intersected in two 300 m diamond drillholes sited 200 m apart. There are large chargeability anomalies in the EM survey area over Kerbar and Conquistador. High zinc grades, base metal and precious metal credits, and large footwall alteration systems have also been intersected at A Zone (e.g. 2.1 m at 2.34% Zn) and Conquistador (6.7 m at 6.0% Zn) (Zenith Minerals Ltd, 2011). Mineralization is hosted in felsic schist relatively close to the contact with underlying mafic schist and occurs over a strike length of about 30 km. SHRIMP U–Pb dating of zircon from a rhyodacite (about 30 km southwest of A Zone) from the Tallering greenstone belt has yielded a mean age of  $2935 \pm 2$  Ma (Pidgeon and Wilde, 1990b).

### **Twin Peaks and Barloweerie greenstone belts**

The Twin Peaks and Barloweerie greenstone belts (Fig. 1b) are two small, mafic-dominated belts in the western Murchison Domain of the Youanmi Terrane. The Twin Peaks greenstone belt can be divided into an older mafic-dominated succession and a younger felsic volcanic succession. Eighty-four tonnes of copper ore averaging 16% Cu was produced from workings north of Twin



**Figure 10.** Geology and mineral occurrences in the Ravensthorpe greenstone belt (southernmost Youanmi Terrane). Base metal occurrences and U–Pb zircon dates are indicated. Geology is based on GSWA (2014a); mineral occurrences are from GSWA (2015b); geochronology is from GSWA (2015a); assemblage boundaries are from Witt (1999)

Peaks Homestead between 1906 and 1960. According to Marston (1979), material on the dump adjacent to the main shaft comprises quartz–muscovite–chlorite schist, biotite–quartz–feldspar schist, biotite granodiorite, thin veins of copper-bearing limonite and copper-stained schist. Base metal mineralization has also been identified along the eastern margin of the greenstone belt at sites such as Breakaway Hills (34 m at 0.4% Zn), Southern Flyer (3.5 m at 1.33% Cu, 2.9 g/t Ag and 0.13 g/t Au) and Tranquility Heights (30 m at 0.6% Zn) (Jabiru Metals, 2010). A felsic volcanic rock taken from the Twin Peaks greenstone belt was dated using U–Pb zircon geochronology by Pidgeon and Wilde (1990b). A maximum  $^{207}\text{Pb}/^{206}\text{Pb}$  age of c. 3014 Ma was considered to be the best estimate for the age of the sample.

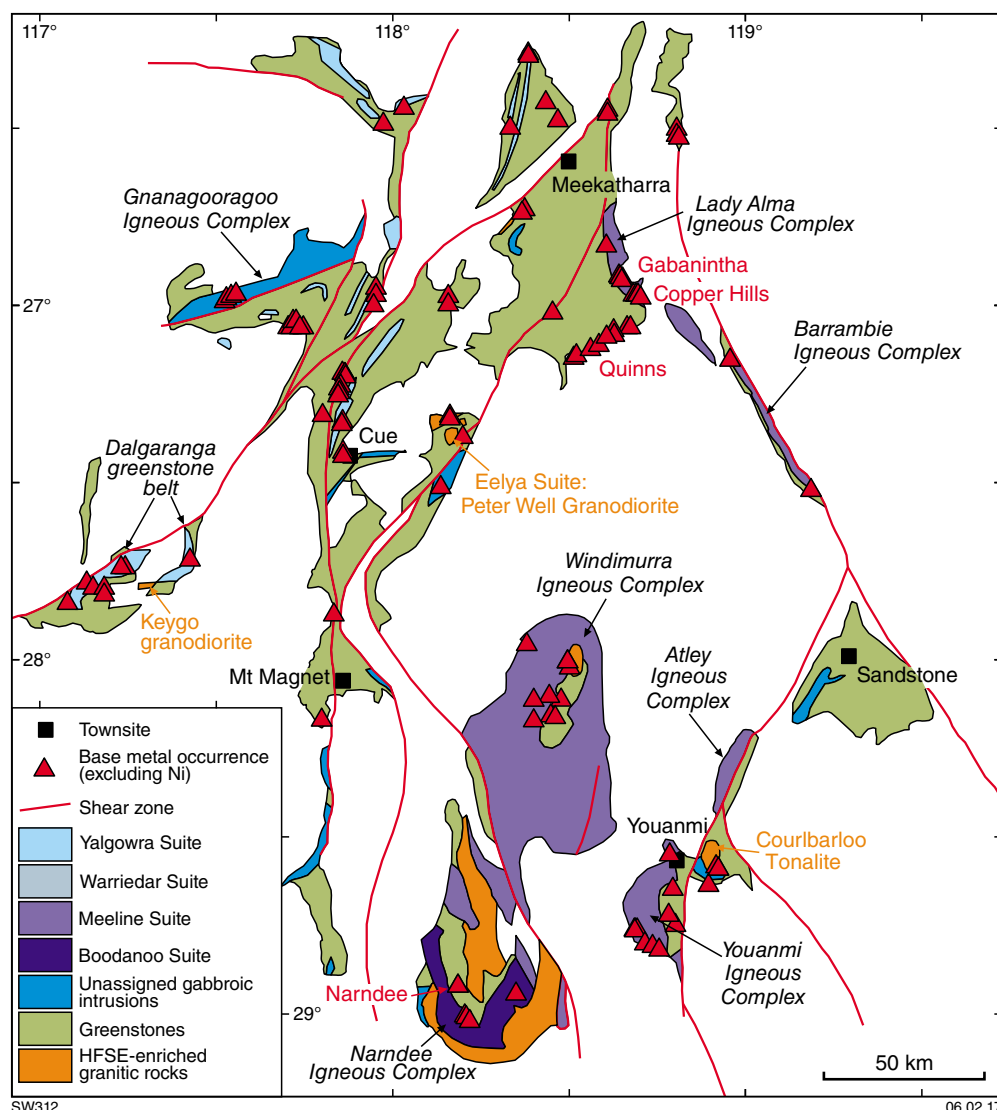
## VMS mineralization in the Norie Group

In the 2825–2805 Ma Norie Group in the northern Murchison Domain (Fig. 3; Van Kranendonk et al., 2013), VMS mineralization at Austin and Chunderloo is associated with petrochemically prospective felsic rocks of the Yaloginda Formation, and at Just Desserts it is associated with a calc-alkaline basaltic unit of the Yaloginda

Formation (Hassan, 2014). Geochemically similar felsic rocks of the Kantie Murdana Volcanics Member, which overlies the Windimurra Igneous Complex in the central Youanmi Terrane (Fig. 11), also host significant VMS mineralization. Significant VMS occurrences have been identified in association with the Narndee, Youanmi, Windimurra and Lady Alma Igneous Complexes.

## Quinns occurrences

Approximately 55 km south of Meekatharra, several significant VMS occurrences have been identified at Quinns (Fig. 12). A mixed succession of banded iron-formation and chert with minor basalt separates a thick succession of felsic volcanic rocks from basalts in the Quinns project area (Fig. 12). There are VMS targets at two stratigraphic levels along 25 km of prospective stratigraphy. The Quinns Project includes the Austin deposit discovered by Silver Swan Group (now Caravel Minerals) in late 2008. Austin has a maiden resource of 1.48 Mt at 1.02% Cu, 1.39% Zn, 3.51 g/t Ag and 0.25 g/t Au, and is amenable to open pit mining. The primary mineral assemblage is dominated by chalcopyrite and sphalerite with gangue pyrite, magnetite and pyrrhotite (Vearncombe, 2011; Silver Swan Group, 2012).



**Figure 11. Distribution of mafic suites and HFSE-enriched granitic rocks in the northern part of the Youanmi Terrane (modified from Ivanic et al., 2010, 2012). Base metal occurrences as in Figure 1b (localities from GSWA, 2015a); granite information from Champion and Cassidy (2002b)**

Significant base metal mineralization has also been intercepted in the Quinns Project area (Fig. 12) along strike at Flinders (6.0 m at 3% Zn), Murchison Wonder (1 m at 5.3% Zn, 0.2% Cu and 9 g/t Ag; and 1 m at 0.7% Zn and 4 g/t Au) and Tasman (6.0 m at 3% Zn, 12 m at 5.5 g/t Ag, 5 m at 0.4% Cu). VMS systems were identified using modern geochemical methods such as: distinctive alteration styles within banded iron-formation units, alteration lithogeochemistry and chlorite chemistry (Silver Swan Group, 2012). For example, at Flinders, altered felsic rocks are significantly enriched in silver, gold, bismuth, copper, indium, gallium, gadolinium, magnesium, molybdenum, lead, sulfur, tellurium, tungsten and zinc. A detailed account of the mineralogy and hydrothermal alteration associated with the Quinns base metal occurrences is presented in Duuring et al. (2016). For an exploration history, see Ferguson (1999).

Zircon from hydrothermally altered felsic volcanoclastic rock (quartz–chlorite–muscovite schist) from a Silver Swan drillhole (Austin area) has been dated at  $2817 \pm 3$  Ma (GSWA 185998, Wingate et al., 2011a), which places the host succession in the VMS-prospective Yaloginda Formation of the 2825–2805 Ma Norie Group.

#### **Yuinmery occurrences (Youanmi greenstone belt)**

There are a number of base metal occurrences in the Youanmi greenstone belt, approximately 75 km southwest of Sandstone (Marston, 1979; Fig. 1). The Just Desserts deposit (Fig. 13) has an inferred and indicated resource of 1.07 Mt at 1.82% Cu and 0.78 g/t Au (Hassan, 2014). Significant mineralization has also been intercepted at the Augustus (18 m at 0.5% Cu), YC14 (5 m at 0.5% Cu, 1.0 g/t Au), Smith Well (8 m at 1.4% Cu, 0.2 g/t Au) and

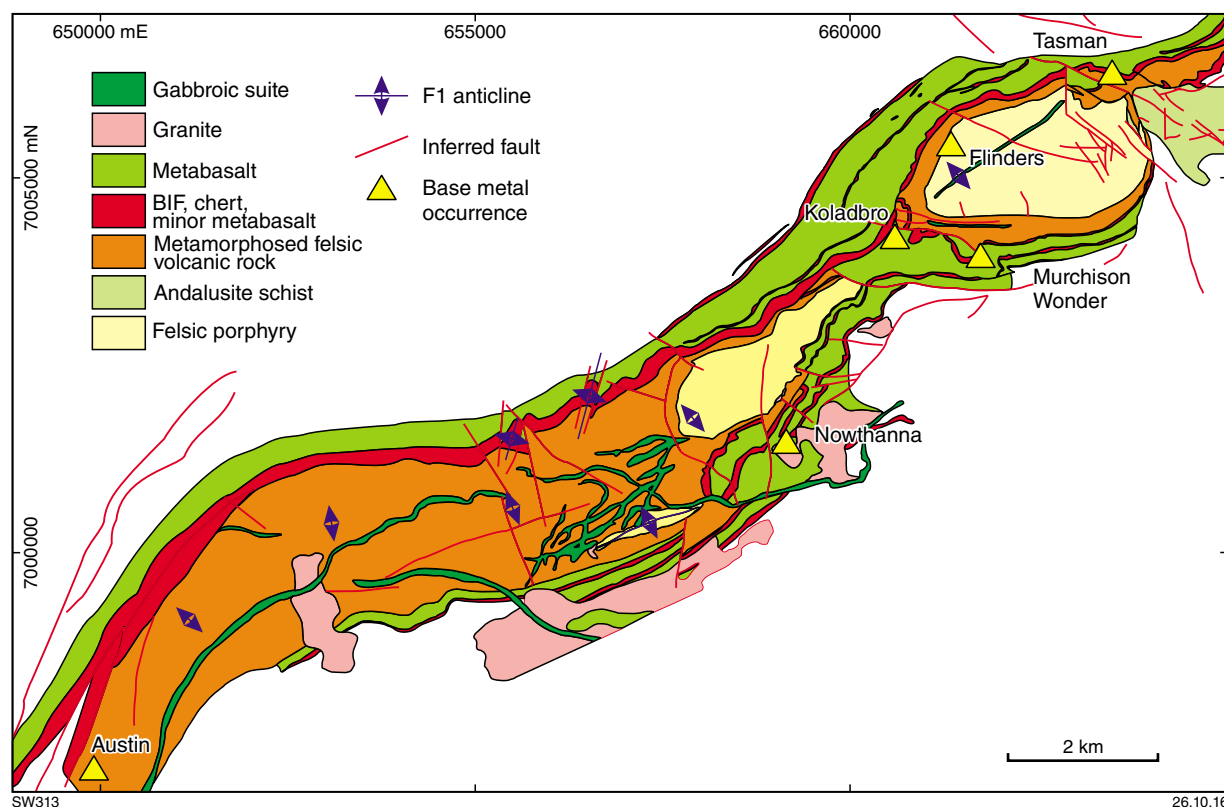


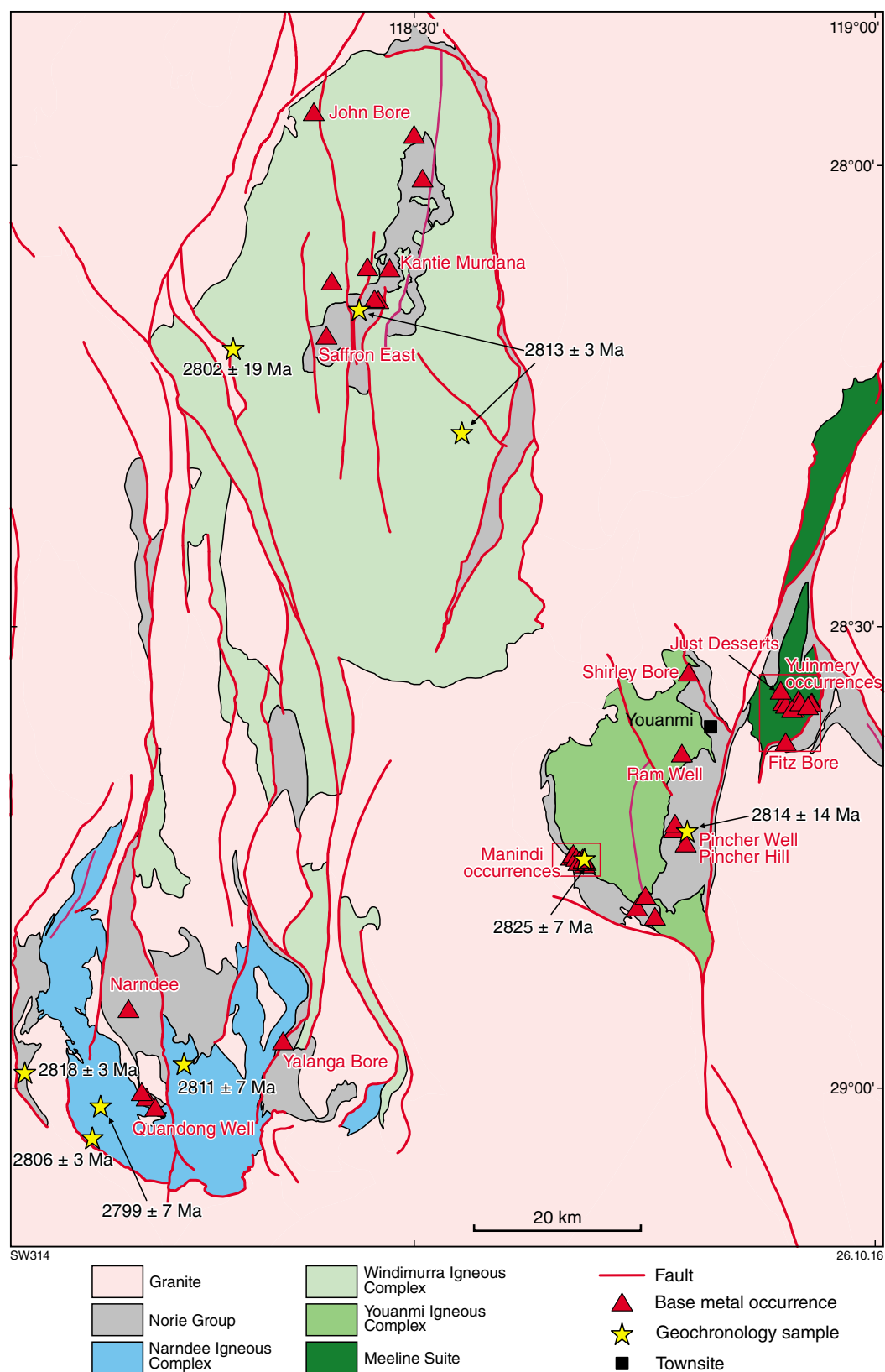
Figure 12. Geology of the Quinns Project area and major VMS occurrences (modified from Silver Swan Group, 2012)

A-zone (7 m at 2.1% Cu, 0.3 g/t Au) prospects (Empire Resources, 2011, 2012). Hassan (2014) presented a detailed mineralogical and geochemical study of the Yuinmery prospects, summarized here. Mineralization is dominated by pyrite, with lesser pyrrhotite, chalcopyrite, sphalerite, magnetite, gold, molybdenite and Bi–Ag–Au–Ni–Co tellurides. The various prospects are hosted in a mixed greenstone sequence that includes calc-alkaline basalt, basaltic hyaloclastite, banded iron-formation, calc-alkaline andesite, tholeiitic basalt and rare rhyolite. Intrusions of gabbro and pyroxenite were also noted. Alteration assemblages are dominated by iron-rich talc at Just Desserts. Other alteration minerals described by Hassan (2014) include chlorite, quartz, Ca-poor amphiboles, minor apatite, ferroan dolomite, white and brown micas, stilpnomelane, hisingerite, and tourmaline. Cumingtonite and anthophyllite are abundant in the banded iron-formation associated with mineralization (Hassan, 2014). SHRIMP U–Pb zircon geochronology from a small tonalitic intrusion five kilometres west of Just Desserts constrains the age of the deposit to  $>2813 \pm 5$  Ma (sample GA 98968104; Fletcher and McNaughton, 2002).

#### Manindi (Freddie Well) occurrences

The Manindi or Freddie Well Zn–Cu deposit is located approximately 100 km southwest of Sandstone and 430 km northeast of Perth (Fig. 13). Discovered in 1972 by gossan targeting, a number of companies have since

investigated the deposit using more modern geological, geochemical and geophysical methods (reviewed in Cornelius and Smith, 2004). Three principal zones of mineralization were targeted, historically referred to as zones A, B and D (Cornelius and Smith, 2004). Mineralization occurs at the southwestern margin of a metamorphosed layered gabbroic complex (Youanmi Igneous Complex), about 20 km southwest of the Youanmi gold mines. These gold mines occur along a north-northwesterly striking, 500 m wide corridor composed of foliated and lineated quartz–sericite(–chlorite–feldspar) schist interposed between the Youanmi gabbros to the east and largely laterite-covered granites to the west (Cornelius and Smith, 2004). The schist is interpreted as derived from a felsic protolith and hosts a series of base metal occurrences along its length, including Felix, Kowari (Zone D south), Kultarr (Zone D north), Numbat, Dunnart, Mulgara (Zone B), Freddie Well Zone C, Warabi (Zone A), Quoll and Bandicoot. Other base metal occurrences are located about 10 km to the east (Pincher Well, Pincher Hill) and about 20 km northeast (Ram Well, Shirley Bore) in similar felsic rocks (GSWA, 2015b). SHRIMP U–Pb dating of zircons interpreted as magmatic from quartz–chlorite schist at Pincher Well ( $2814 \pm 14$  Ma, GSWA 169067, Nelson, 2002) indicates the host succession formed at the same time as the VMS-prospective Yaloginda Formation of the 2825–2805 Ma Norie Group (Van Kranendonk et al., 2013).



**Figure 13. Geology and mineral occurrences of the Narndee, Windimurra, Youanmi and Yuinmery areas (northern Youanmi Terrane). Geology is based on GSWA (2014a); mineral occurrences are from GSWA (2015b); geochronology is from GSWA (2015a)**



At Manindi, the eastern margin of the felsic schist is sulfidic and contains a number of pods and semi-continuous horizons of rutilated, gahnite-bearing, quartz-rich rock (informally termed 'freddite') that may represent recrystallized chert or banded iron-formation (Cornelius and Smith, 2004). This rock changes facies along strike into banded quartz–magnetite rock and also contains lenses of massive sulfides, mainly pyrrhotite, pyrite and sphalerite, with or without magnetite (Cornelius and Smith, 2004). Some lenses are characterized by up to 50% sphalerite and minor chalcopyrite. Recent exploration has substantially upgraded the Manindi deposit, for a resource of 1.08 Mt at 6.52% Zn, 0.26% Cu and 3.19 g/t Ag (Metals Australia Ltd, 2015). The resource occurs in 4 main zones: Warabi (Zone A), Mulgara (Zone B), Kowari (Zone D south) and Kultarr (Zone D north).

### **Narndee occurrences**

At Narndee, approximately 115 km southeast of Mount Magnet (Fig. 13), the c. 2800 Ma Narndee Igneous Complex (Ivanic et al., 2010) of layered mafic–ultramafic rocks is overlain by felsic volcanic rocks of the Norie Group (Fig. 3), which show potential for significant VMS mineralization (Fig. 13). Common copper-anomalous gossans are stratabound within deformed and metamorphosed felsic volcanic rocks and associated sedimentary rocks (quartz–mica–chlorite schists) including chert and banded iron-formation (Marston, 1979). Following a REPTeM survey, drilling in 2012 by Maximus Resources identified two EM anomalies coincident with gravity anomalies, and two zones of zinc-rich VMS mineralization (Maximus Resources, 2012). Results include 10 m at 1% Zn (including one metre at 5.89% Zn; Maximus Resources, 2012). Other base metal occurrences associated with the Narndee Igneous Complex include Yalanga Bore and Quandong Well A, B and D (GSWA, 2015b). From immediately north of Quandong Well, Marston (1979) reported intersections of 9 m at 1.3% Cu from gossanous quartzite – banded iron-formation. Mineralization is dominated by iron sulfides and higher copper and zinc grades are found in fold hinges.

SHRIMP U–Pb zircon geochronology in the Narndee area has yielded an age of  $2799 \pm 7$  Ma from gabbro-norite (GSWA 191056, Ivanic et al., 2010), and  $2818 \pm 3$  Ma from an andesite 20 km west of the base metal occurrences (GSWA 193979, Wingate et al., 2012c).

### **Other**

There is also a strong temporal and spatial relationship between mafic intrusive complexes and overlying VMS-prospective felsic volcanic rocks of the Meeline and Boodanoo Suites (Fig. 3), which most likely provided sufficient heat to drive hydrothermal circulation in the upper crust. At Windimurra, the Saffron East, Ann, Rosemary, Kantie Murdana base metal occurrences overlie the c. 2813 Ma Windimurra Igneous Complex of the Meeline Suite (GSWA 194747, Wingate et al., 2012d). At Copper Hills (northeast of Quinns), base metal occurrences are associated with the Lady Alma Igneous Complex (Silver Swan Group, 2012) (Fig. 11; GSWA, 2015b).

## **Mineralization in the Polelle Group**

In the 2800–2735 Ma Polelle Group, all significant VMS occurrences are hosted by the Greensleeves Formation (Fig. 3).

### **Hollandaire (east of Cue)**

Although some base metal exploration, including mapping, geochemical sampling and some drilling, was undertaken in the region east of Cue during the 1970s, the area around Mount Eelya has largely been overlooked for base metal mineralization since 1981. In September 2011, the Hollandaire VMS deposit was discovered about 30 km northeast of Cue by Silver Lake Resources (Figs 11, 14; Musgrave Minerals Ltd, 2016). Mineralization (0.4 Mt at 1.15% Cu, 0.6 Mt at 7.9 g/t Ag and 0.8 g/t Au) is hosted in a succession of turbidites, mudstones and coherent rhyodacite sills. The following description is based on Hayman et al. (2015). There are two main orebodies: Hollandaire Main (~125 x 500 m, 5–8 m thick and open at depth) and Hollandaire West (~100 x 470 m, 5 m thick). Massive sulfides occur exclusively in turbidites and mudstones, with only stringer and disseminated sulfides present in coherent rhyodacite. An upper oxide zone enriched in gold extends to ~50 m below the surface (Hayman et al., 2015). Mineralization is dominated by chalcocite with bornite and covellite in the oxide zone, whereas in primary massive sulfides at depth mineralization is characterised by pyrite, chalcopyrite with lesser sphalerite and galena. Hydrothermal alteration has resulted in Mg, Mn and K gains around the deposit and losses in Na, Ca and Sr. Garnet and staurolite porphyroblasts are distributed 30 m above and below the ore zone.

According to the stratigraphy of Van Kranendonk et al. (2013), the Hollandaire deposit is located in the 2800–2735 Ga Polelle Group. A SHRIMP U–Pb zircon date for a rhyolite from Eelya Hill ( $2746 \pm 4$  Ma, GSWA 185932, Wingate et al., 2012a) places the succession in the felsic-dominated Greensleeves Formation (Figs 3, 14). This is supported by a TIMS (thermal ionisation mass spectrometry) U–Pb zircon age of  $2759.5 \pm 0.9$  Ma from coherent rhyodacite at Hollandaire (Hayman et al., 2015). Regionally, granitic rocks of the Eelya Suite (Fig. 14) are broadly coeval to VMS hosting felsic rocks, and may represent a potential heat source that facilitated VMS mineralization (Hayman et al., 2015). The HFSE-enriched Peter Well Granodiorite (Fig. 11), about 28 km northeast of Cue, has yielded a U–Pb zircon age of  $2747 \pm 6$  Ma (Wang, 1998). Similar dates have been obtained from closely associated monzogranite ( $2749 \pm 6$  Ma, Wang, 1998) and biotite granite ( $2759 \pm 3$  Ma, GSWA 185933, Wingate et al., 2010b).

### **Mount Mulcahy (north of Cue)**

The Mount Mulcahy area (Fig. 9), approximately 50 km north of Cue, was historically targeted for base metal mineralization over several decades (Marston, 1979). Mineralization is present on both the northern and southern limbs of an east-dipping syncline. Two gossans,



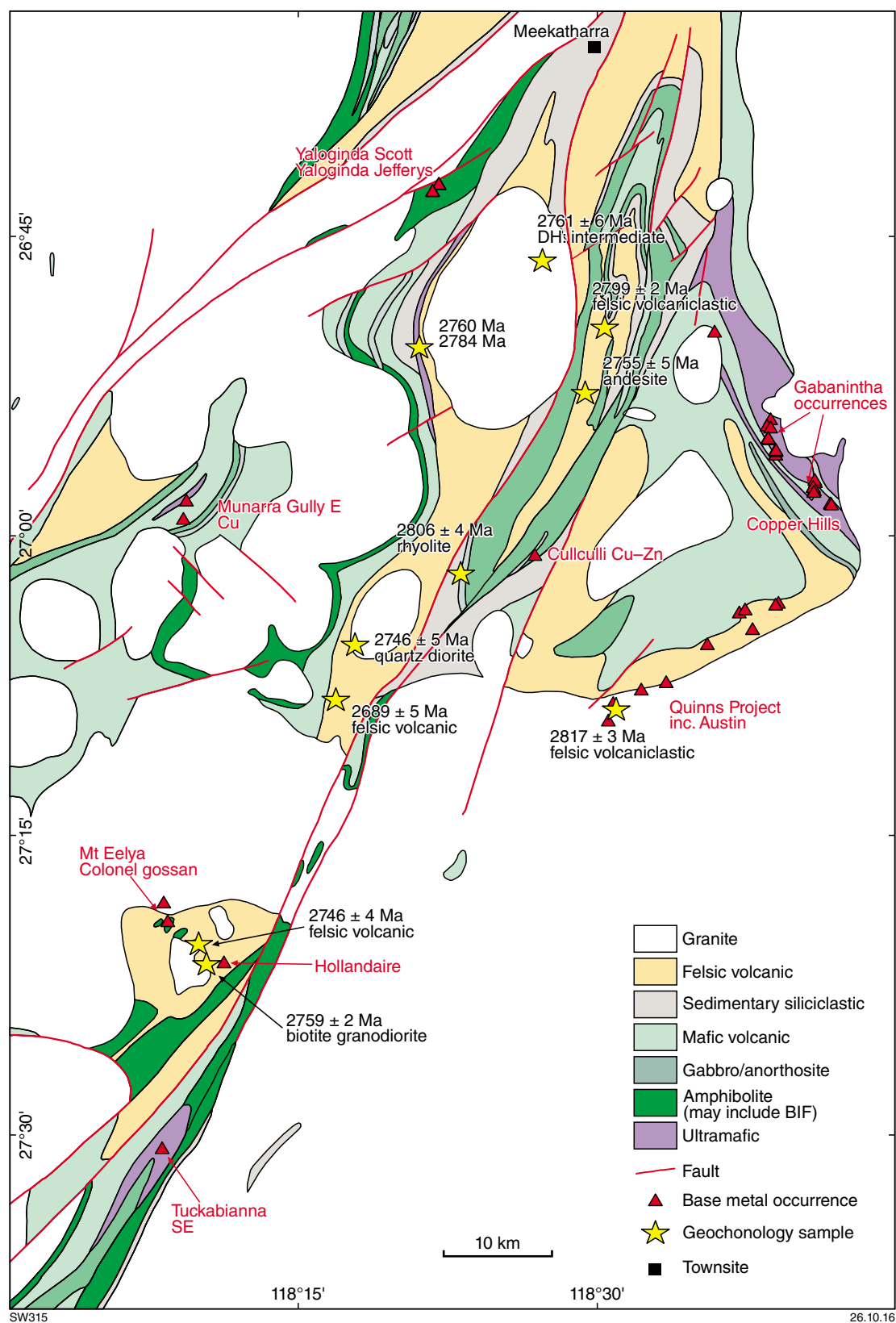


Figure 14. Geology and mineral occurrences in the northern Murchison Domain around Hollandaire, Quinns and Copper Hills. Geology is based on GSWA (2014a); mineral occurrences are from GSWA (2015b); geochronology is from GSWA (2015a)

approximately 750 m apart, occur in a thin sedimentary and tuffaceous package. Mineralization is hosted in finely laminated, chert-like sedimentary rocks, quartz-sericite phyllite, black shale, and silicic volcanic rocks, at or close to the contact with overlying basalts (Marston, 1979). This assemblage forms a minor component in a succession dominated largely by mafic igneous rocks. The westernmost gossan produced a small tonnage of cupreous ore between 1954 and 1965 (Marston, 1979). Additional mineralization was identified in the area between 1969 and 1972 when a consortium discovered nine kilometres strike length of sporadic mineralization using surface geochemistry and systematic percussion drilling (Marston, 1979). Pegasus Minerals (2014) announced a maiden JORC resource at Mount Mulcahy of 647 000 t at 2.3% Cu for 15 200 t Cu, 1.8% Zn for 11 900 t Zn and 20 g/t Ag for 415 000 oz Ag. The resource is based on 90 drillholes totalling 11 461 m. Mineralization is on the southern limb of a syncline and hosted in a massive sulfide horizon ranging from less than one metre to 10 m thick. The hangingwall is a black shale and shale unit and the footwall is gabbro and basalt. Other base metal occurrences nearby include Seivwright, Wilgie Mia and McCarthy (GSWA, 2015b).

Van Kranendonk et al. (2013) placed the Mount Mulcahy area supracrustal rocks into the 2800–2735 Ma Polelle Group. A younger layered gabbroic complex intrudes the mafic dominated succession and has been attributed to the c. 2720 Ma Yalgowra Suite (Ivanic et al., 2010).

### **Emily Well occurrences (west of Cue)**

Two occurrences of base metal have been reported approximately nine kilometres northwest of Cue (Fig. 9): Emily Well W (GSWA, 2015b, site S0033058) and Emily Well SW (GSWA, 2015b, site S0033160). The best intersection to date is 4 m at 1.45% Cu, 1.6% Zn, and 1087 ppm Pb at Emily Well SW (which includes 2 m at 2.5 g/t Au and 18 g/t Ag; GSWA, 2015b, site S0033160). The stratigraphy at Emily Well comprises rhyolitic to dacitic volcanic and volcanoclastic rocks near major fault or shear systems. Van Kranendonk et al. (2013) assigned this area to the 2800–2735 Ma Polelle Group. Two samples of rhyolitic crystal-vitric tuff taken 1.5 km apart from near Emily Well have produced U–Pb zircon ages of  $2761 \pm 1$  Ma and  $2761 \pm 4$  Ma (Pidgeon and Hallberg, 2000), placing the volcanic succession near the base of the 2761–2735 Ma Greensleeves Formation (Fig. 3; Van Kranendonk et al., 2013).

### **Dalgaranga greenstone belt**

There are several base metal occurrences in the Dalgaranga greenstone (Fig. 1b) belt, about 75 km west-northwest of Mount Magnet. These include the Phoebe (Zn), Gum Well 1 and 2 (Zn–Cu–Ag), and the Dalgaranga Hill prospects (Zn). The Lasoda prospects (Pb–Zn–Cu–Ag) also lie about 6 km to the northeast in a more felsic-dominated part of the belt (Fig. 15). At Dalgaranga, the volcanic succession is characterized by greenschist-facies metamorphic rocks, and is dominated by felsic volcanic rocks with tholeiitic flows up to 300 m thick, overlain by

carbonaceous sericite schist, shale and siltstone, grading into an oxide–silicate facies banded iron-formation (Butt and Sergeev, 2003). Two large, layered gabbro sills intrude the greenstone succession. Sedimentary and felsic units are metamorphosed to quartz–andalusite–muscovite–biotite schists adjacent to granitic rocks. Several felsic tuffaceous rocks from the Dalgaranga greenstone belt were dated using U–Pb geochronology by Pidgeon and Hallberg (2000). All U–Pb ages are similar at c. 2745 Ma (Fig. 15). Those from Lasoda also contained a >2900 Ma zircon population. A differentiated gabbro sill dated by Pidgeon and Hallberg (2000) has a U–Pb zircon age of  $2719 \pm 6$  Ma and belongs to the Yalgowra Suite (Fig. 3).

The Dalgaranga base metal prospects were originally discovered by rock and gossan chip surveys, ground magnetic and EM surveys, and shallow drilling in the early 1970s (Butt and Sergeev, 2003). CRA Exploration Pty Ltd (CRAE) carried out the largest and most comprehensive grassroots program, targeting felsic-hosted VMS mineralization similar to that at Golden Grove. Sixteen base metal anomalies were identified, four of which were explored in detail. Although various companies have held tenements over the greenstone belt since, no significant VMS deposits have been discovered. Drill intersections into fresh rock returned disappointing assay values with base metal values rarely exceeding half a percent. Sulfide assemblages were dominated by pyrrhotite (50–90%) with minor sphalerite, chalcopyrite and pyrite, with traces of galena and bismuth–tellurium sulfides (Butt and Sergeev, 2003).

Mineralization at the Superior zinc prospect (Fig. 15), north of the Dalgaranga Hill gabbro, is hosted in steeply dipping schists, which are locally graphitic (Butt and Sergeev, 2003). These schists are characterized by muscovite and quartz with minor biotite, chlorite and plagioclase, and large porphyroblasts of andalusite. Intersections of disseminated and semi-massive sulfides include 26 m at 1% Zn, 0.14% Cu and 0.02% Pb, although most drilling was shallow and little primary sulfide mineralization was located (Butt and Sergeev, 2003). At Lasoda, K, Ca and Mg enrichment is associated with carbonate and chlorite and Al-silicates, corresponding to a zone of Na-depletion, typical of VMS alteration. It appears that detailed trace-element geochemical techniques have not been applied in the Dalgaranga greenstone belt. Geophysical techniques demonstrated to work elsewhere in the Yilgarn (e.g. Jaguar) may be fruitful. Regolith geochemistry over the Dalgaranga prospects reveals several areas of interest which have not been fully tested (Butt and Sergeev, 2003).

### **Wattagee Well occurrences (north of Cue)**

Several copper–zinc–lead anomalous gossans, between 22 and 30 km north of Cue in the Murchison Domain (Youanmi Terrane), have been targeted since 1969 (Marston, 1979). At Wattagee Well (Fig. 9), base metal mineralization occurs for about eight kilometres along strike and is hosted by a north-northeasterly trending succession. Mineralization is hosted in a fine-grained, quartz–muscovite or chlorite-altered phyllite or schist, and carbonaceous phyllite. These rocks form a minor

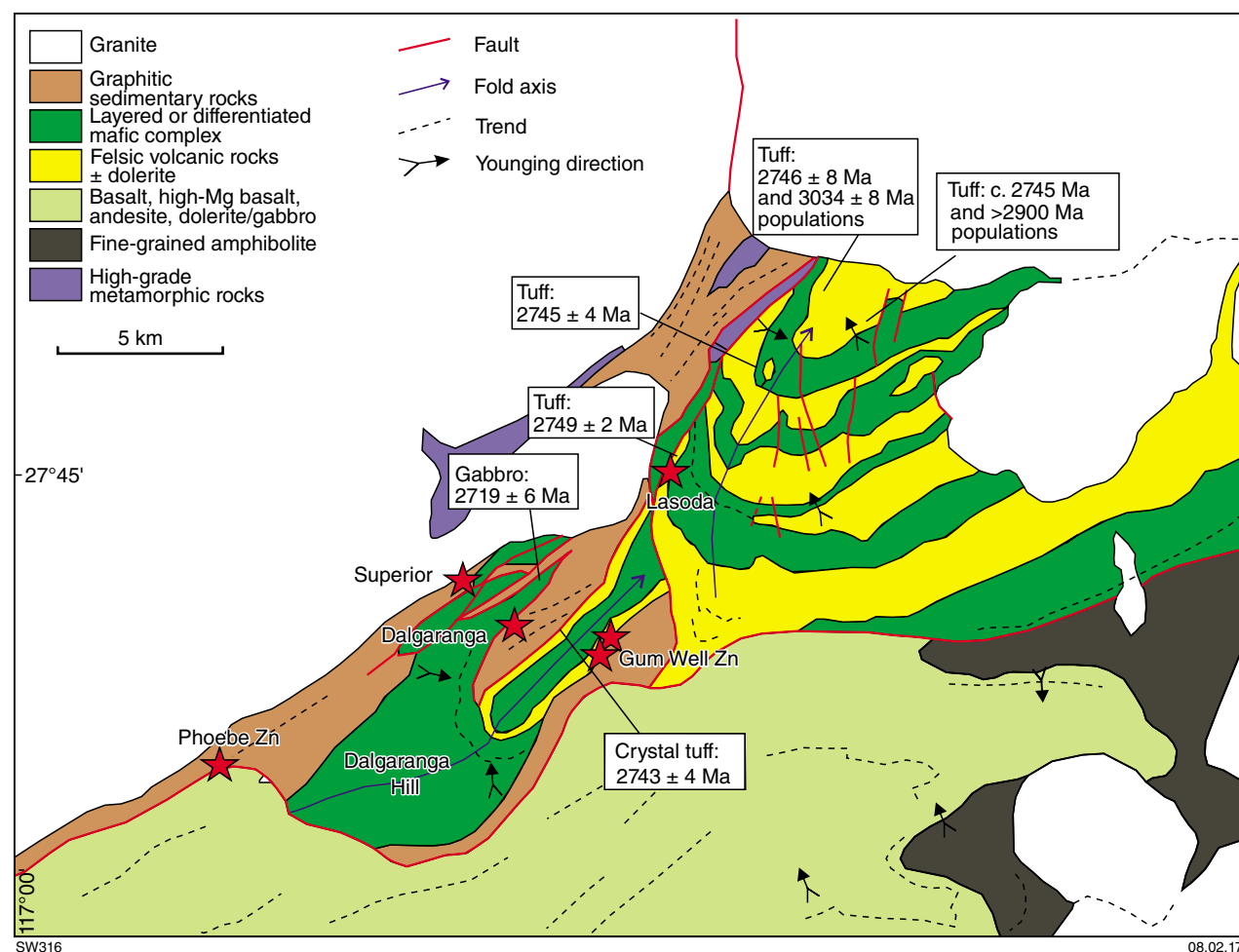


Figure 15. Simplified geology of the western Dalgarna greenstone belt with U-Pb geochronology and base metal localities (modified from Pidgeon and Hallberg, 2000)

component of the local stratigraphy, which is dominated by feldspathic basalts and amygdaloidal basalts intruded by gabbroic sills of the Yalgowra Suite (Fig. 3). While drilling in the north has yielded disappointing results (e.g. massive pyrrhotite with low copper-zinc), zinc-rich mineralization has been identified to the south (3 m at 7.5% Zn: Marston, 1979). See Ferguson (1999) for additional information on the exploration history at Wattagee Well.

Van Kranendonk et al. (2013) placed the host succession for the Wattagee Well prospects in the Polelle Group. Approximately 16 km south-southwest of Wattagee Well, U-Pb zircon dating of a leucogabbro sill (Fleece Pool Gabbro) of the Yalgowra Suite has yielded an age of  $2735 \pm 5$  Ma (GSWA 185922, Wingate et al., 2010a), suggesting the host sequence is older. To the northwest of Wattagee Well, a sample of rhyolite (quartz-sericite schist) has yielded a U-Pb zircon age of  $2725 \pm 4$  Ma (GSWA 83975, Wingate et al., 2009). This rhyolite forms part of the overlying c. 2720 Ma Glen Group (Van Kranendonk et al., 2013). Volcaniclastic andesite at Wattagee Hill has been correlated with the Woolgra Andesite, which suggests the felsic rocks are of similar age to the Greensleeves Formation.

## VMS mineralization in the 2735–2700 Ma Glen Group

VMS mineralization has not been identified in the 2735–2700 Ma Glen Group in the Murchison Domain. However, several occurrences have been discovered in rocks of similar age in the Gum Creek greenstone belt (Fig. 1b).

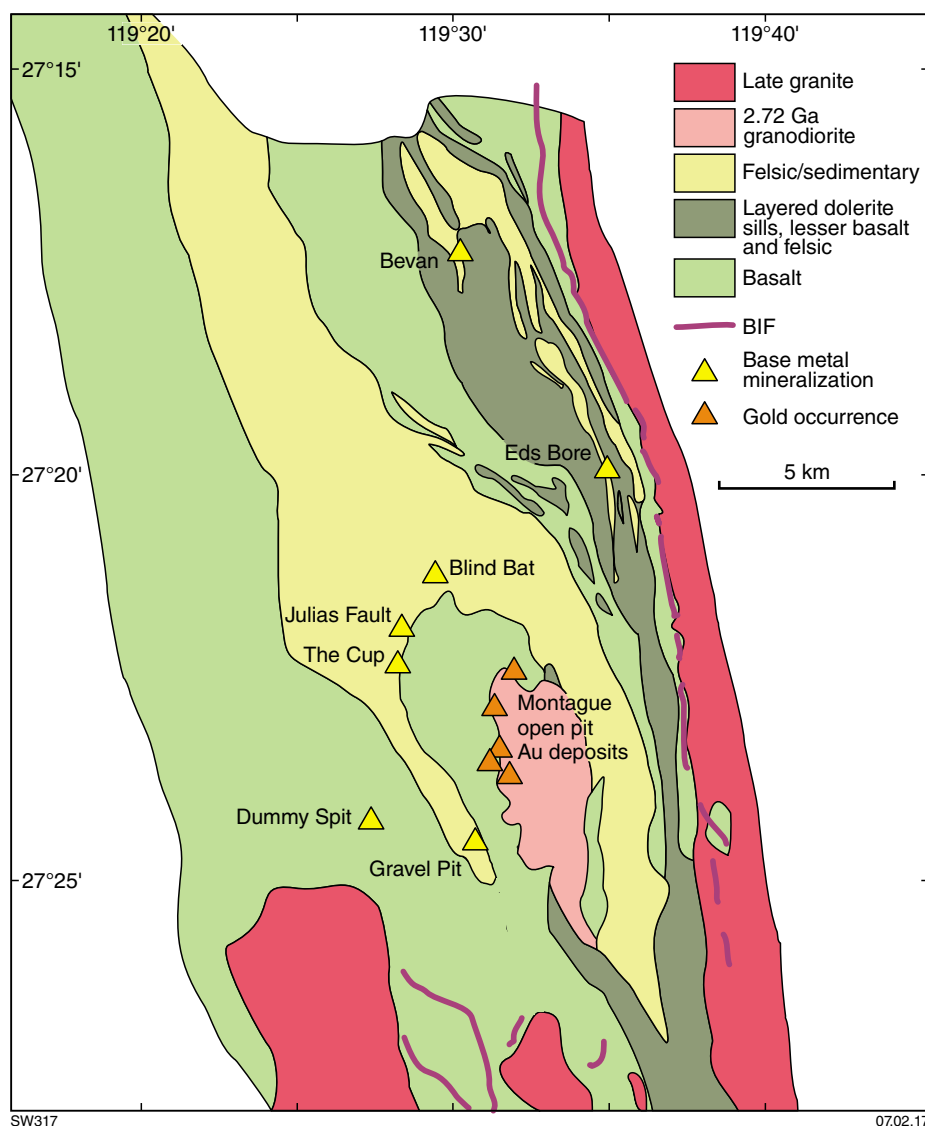
### Gum Creek greenstone belt

In the Gum Creek greenstone belt of the Southern Cross Domain (Fig. 16), base metal occurrences have been targeted by exploration companies for a few decades. Most are restricted to the eastern side of the belt where mixed felsic volcanic and sedimentary packages and synvolcanic sills are more common (Beeson et al., 1993). In the far eastern part of the belt (Montague Range 'Domain' of Beeson et al., 1993), base metal mineralization shows a close spatial correlation with carbonaceous shales. Located 300 m north of Eds Bore, the uppermost shale horizon (Beeson et al., 1993) is associated with a prominent gossan and zinc mineralization (3 m at 3.65% Zn in diamond drilling). Farther north, a stratigraphically lower shale

horizon also contains supergene base metal mineralization at Bevan, although historic diamond drilling failed to intersect this zone below the supergene blanket. The felsic-dominated host sequence at Bevan has yielded a U–Pb zircon age of  $2722 \pm 6$  Ma (GSWA 179239, Bodorkos et al., 2006). Beeson et al. (1993) reported several minor mineralized localities within a felsic volcano-sedimentary succession and interfingering, but mostly overlying, clastic sedimentary rocks in their Lake Mason ‘Domain’ in the western part of the Gum Creek greenstone belt.

Gateway Mining (2012) has identified several base metal prospects in the Gum Creek greenstone belt including The Cup, Gossans Galore, Blind Bat, Julius Fault, Dummy Spit and Gravel Pit (Fig. 16; Gateway Mining, 2012). The Cup, discovered by Gateway Mining in late 2006 using rock-chip, historical aircore and RAB geochemistry, is hosted in a mixed intermediate to felsic package near a contact with basalt and fine-grained sedimentary rocks (siltstone and carbonaceous shale). The host sequence is

associated with sericitic to chloritic alteration (Gateway Mining, 2012). Intercepts at The Cup include 80 m at 0.66% Cu. Drilling has revealed a zonation from copper- to zinc-rich mineralization with silver and arsenic also being anomalous (Gateway Mining, 2012). Mineralization is associated with pyrite-dominated semi-massive to massive sulfides, of which chalcocite is the primary copper-bearing mineral at The Cup due to supergene alteration. At Gravel Pit, a gossan has been intersected by aircore drilling, and RAB drilling geochemistry revealed anomalous antimony, copper, and zinc in graphitic shales with rare pyrite (Gateway Mining, 2012). There are several parallel linear EM anomalies in the area which correspond with carbonaceous sedimentary rocks, the easternmost of which is interpreted as an along-strike continuation of The Cup trend (Gateway Mining, 2012). Gossans Galore is similarly characterized by linear EM anomalies, gossans, and coincident sulfides. Anomalous base metal values and VMS pathfinder haloes have also been noted from aircore drilling.



**Figure 16. Geology and mineral occurrences in the southern Gum Creek greenstone belt (adapted from Gateway Mining, 2016)**

## VMS mineralization of uncertain age

Other VMS occurrences in the Youanmi Terrane, hosted in successions which lack U–Pb zircon age and stratigraphic constraints, are listed below.

### **Mount Alfred (Illaara greenstone belt)**

The Mount Alfred prospect in the central Southern Cross Domain, approximately 110 km southeast of Sandstone, is in a layered succession of quartz–feldspar–chlorite-altered schist, graphitic sedimentary rocks, chert, banded iron-formation and mafic igneous rocks of the Illaara greenstone belt (Marston, 1979). According to Marston (1979), assays yielded up to 19% Cu from chlorite schist which is associated with pyritic siltstone and a magnesite cap, both of which have yielded moderate copper assays (to 1 and 4% Cu, respectively).

### **Bunnawarra and associated prospects (west of Golden Grove)**

A number of base metal occurrences have been recognized in the Gullewa greenstone belt, approximately 50 km west of the Golden Grove belt (Fig. 1b). These include, from north to south (discounting those associated with nickel): Whelock (Cu–Au), the Bunnawarra/Edamurta (Cu–Zn) prospects (Cu), Buddadoo (Cu–Au–Zn), Yallabyne Hill (Cu–Zn–Pb) and zinc mineralization at Gullewa.

Historic workings at Bunnawarra consist of pits and shallow open pits in chlorite schist. Mineralization is stratabound in a thin succession of laminated quartzite, chlorite–quartz–sericite schist and quartz–chlorite–garnet amphibolite, and occurs as copper-stained quartz veins and thin mineralized zones of limonite-cemented quartz breccias (Marston, 1979). A few tonnes of copper ore were produced in the 1960s (Marston, 1979). According to Marston (1979), diamond drilling by Unimin revealed zinc-rich mineralization in structurally higher quartz–sericite breccias and sericitic quartzite, and stratiform and disseminated copper-rich mineralization in a structurally lower quartz–chlorite–sericite(–garnet) schist and quartzite (3.15 m at 3.8% Cu).

At Buddadoo, past drill targets included 5.5 m at 3.4% Zn and 3.15 m at 3.8% Cu (Coziron Resources Ltd, 2012). There are no published age constraints in this region. See Ferguson (1999) for additional information on the Bunnawarra and associated prospects.

### **Copper Bore occurrences**

In the Marda–Diemals greenstone belt in the central Southern Cross Domain (Fig. 1b), many drill targets have been identified between Copper Bore and Southern Gossan (Fig. 17), approximately 190 km south of Sandstone (Copper Bore Project; Southern Cross Goldfields Ltd, 2012). Mineralization (Cu–Zn–Au–Ag) is associated with a 5–10 m thick package of shales between high-Mg (including pyroxene spinifex-textured komatiitic) basalts and undifferentiated gabbro sills (Chen et al., 2003).

The prospective stratigraphy has a strike length >20 km (Southern Cross Goldfields Ltd, 2012). In tenements explored by Southern Cross Goldfields Ltd (2012), VMS targets have been identified along about 10 km of strike and include Copper Bore (e.g. 4 m at 3.05% Cu, 0.72 g/t Au), Southern Gossan (e.g. 8 m at 8.25% Cu and 2.05 g/t Au) and Kim Bore (e.g. 4 m at 2.45% Zn and 8.6 g/t Ag). Downhole EM techniques have been successful in identifying new zones of massive sulfide at Southern Gossan and the mineralized zone extends 350 m below the surface and 150 m along strike, and remains open in all directions (Southern Cross Goldfields, 2012). Mineralization is marked by a surface gossan which has yielded assay values up to 23.3% Cu and 14.9 g/t Au. At Kim Bore, ground EM results are coincident with both the Copper Bore VMS trend and soil anomalies (Southern Cross Goldfields, 2012).

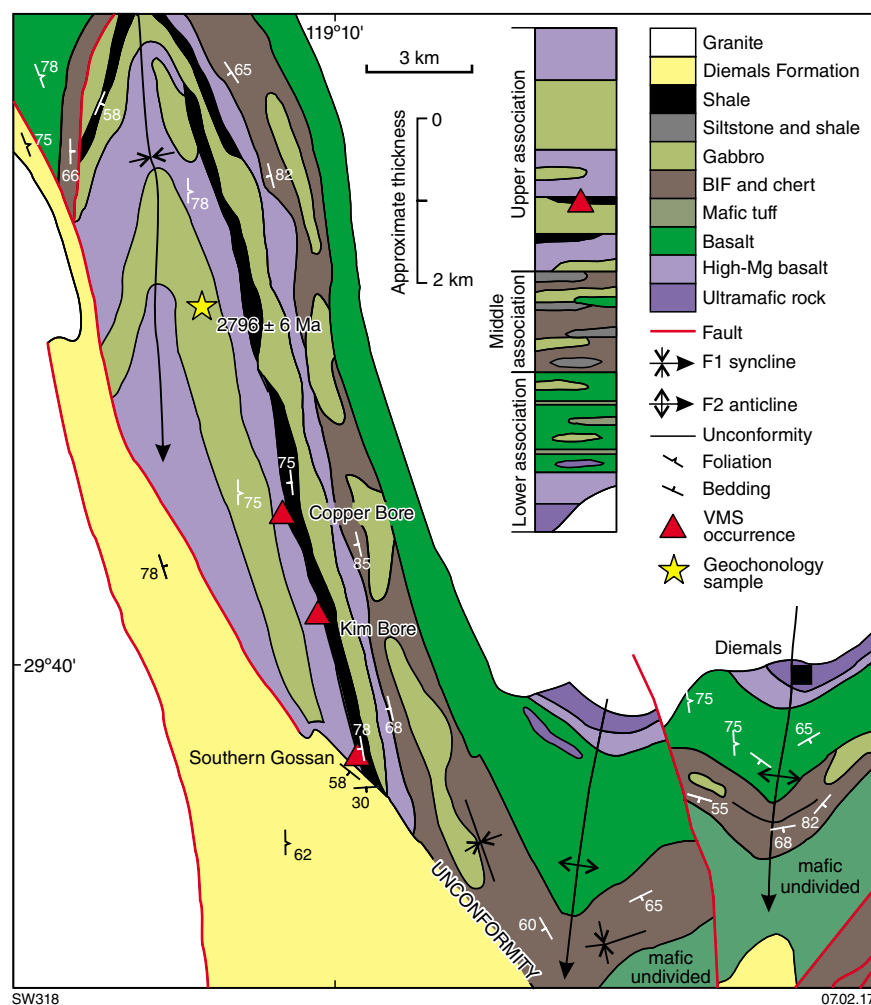
There are few geochronological constraints for the Marda–Diemals greenstone belt. The stratigraphy is divided into three associations in the lower greenstone succession using laterally continuous banded iron-formation and chert units as marker horizons (Chen et al., 2003). Although Chen et al. (2003) suggested the succession may be 3.0 Ga in age, a coarse-grained to pegmatitic leucocratic gabbro from about eight kilometres along strike of Copper Bore has yielded a U–Pb zircon age of  $2796 \pm 6$  Ma (GSWA 185990, Wingate et al., 2011b). This unit belongs to the Grass Flat Gabbro (Riganti et al., 2010) and is one of two large layered gabbroic sills in the area. The dated sample was taken from the uppermost gabbro which intrudes komatiitic basalts in the hangingwall of the VMS-associated shales. Further U–Pb geochronology is needed to constrain the age of the host succession. It is unclear how the succession relates to those in the Murchison Domain.

## Eastern Goldfields Superterrane

Apart from in the central Kurnalpi Terrane, which hosts significant VMS mineralization around Teutonic Bore, most areas of the Eastern Goldfields Superterrane appear to be relatively impoverished in VMS mineralization and, compared with the Youanmi Terrane, few base metal occurrences having been discovered (Fig. 1b). However, the upgrading of the Nimbus deposit and significant mineralization at Anaconda (Fig. 18) and Erayinia/King (Fig. 1b) highlight the potential for additional discoveries. The prospectivity of the Eastern Goldfields Superterrane is discussed below under ‘Prospectivity of the Yilgarn Craton’.

### **Teutonic Bore Camp**

The discovery in the mid-1970s of VMS mineralization at Teutonic Bore (Fig. 18), approximately 60 km north of Leonora represented the second major VMS find in the Yilgarn Craton. Three VMS deposits have now been mined in the area (Fig. 19; Hollis et al., 2015): Teutonic Bore (1.68 Mt mined at 10.7% Zn, 3.5% Cu, 140 g/t Ag), Jaguar



**Figure 17. Geology of the Diemals area of the Southern Cross Domain, lithostratigraphy and approximate positions of VMS occurrences (modified from Chen et al. 2003). Geochronology from Wingate et al. (2011b)**

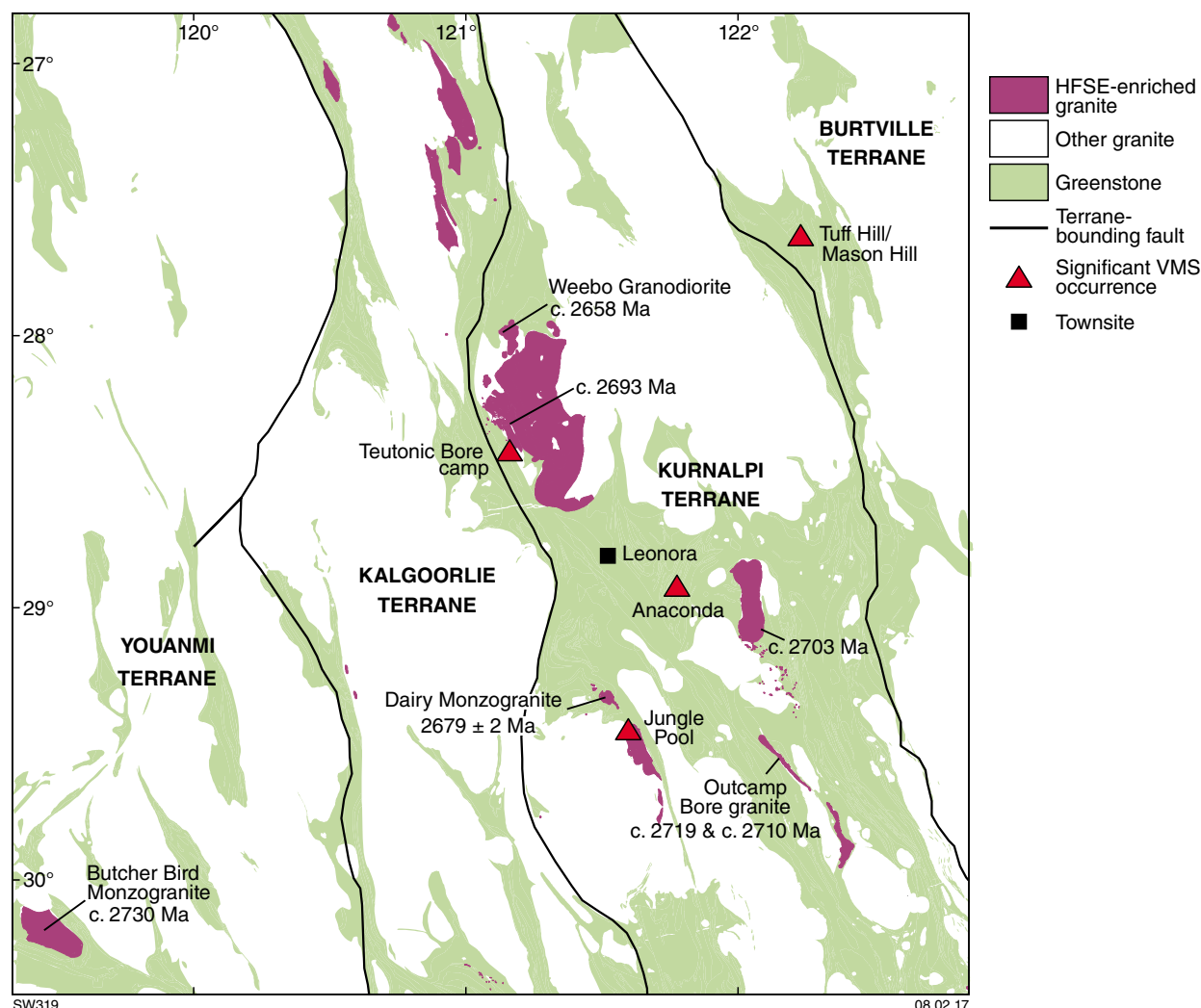
(1.60 Mt pre-mining reserve at 11.3% Zn, 3.1% Cu, 115 g/t Ag) and Bentley (3.05 Mt pre-mining resource at 9.8% Zn, 2.0% Cu, 139 g/t Ag, 0.7 g/t Au). The Teutonic Bore area has regional significance with respect to the Eastern Goldfields Superterrane due to the presence of petrochemically favourable felsic volcanic rocks and synvolcanic growth faults, and its close association with HFSE-enriched granites (Fig. 18; Hallberg and Thompson, 1985; Witt et al., 1996; Brown et al., 2002; Barley et al., 2008).

### Teutonic Bore

In 1979, the decision to mine the Teutonic Bore VMS deposit was reached based on an initial reserve of 2.17 Mt at 3.5% Cu, 11.3% Zn, 0.9% Pb and 150 g/t Ag. Mining commenced in 1981 and ceased in October 1984 (Ellis, 2004). Massive sulfide mineralization at Teutonic Bore is hosted by a thin black shale, chert and tuffaceous epiclastic sedimentary succession that overlies about 100 m of pillowed basalt and andesite with minor interlayered sedimentary rocks. This succession in turn overlies a thick succession of rhyolite lavas and

fragmental rocks (Fig. 20; Greig, 1984). Massive sulfide mineralization occurs as a conformable banded lens about 320 m long, 280 m down-dip and up to 30 m thick (Fig. 20), composed of pyrite, sphalerite, chalcopyrite and galena. This is underlain by a stringer zone (0.75 Mt at 2.38% Cu, 1.92% Zn and 52 g/t Ag) characterized by pyrite, chalcopyrite and sphalerite. The discordant feeder pipe is characterized by quartz–chloritoid–paragonite and cuts across a semi-conformable hydrothermal assemblage of quartz–sericite–chlorite–carbonate, which underlies and extends laterally away from the deposit (Large, 1992). There is intense silicification in the centre of the feeder pipe, directly below massive sulfide mineralization. The feeder zone is depleted in Ca, Na and Sr, and enriched in Fe ( $\pm$  Mg), K and Al (Greig 1984). For further detail on the Teutonic Bore deposit, see Greig (1984), Hallberg and Thompson (1985) or Large (1992). A sample of felsic volcanic rock collected one kilometre northwest of Teutonic Bore was dated at  $2688 \pm 4$  Ma (Pidgeon and Wilde, 1990b). Dacite from a felsic extrusive rock near the deposit has yielded a U–Pb zircon age of  $2692 \pm 4$  Ma (GSWA 112159, Nelson 1995a).





**Figure 18. Distribution of HFSE-enriched granitic rocks in the Eastern Goldfields Superterrane (modified from Hollis et al., 2015). Granite information is from Cassidy and Champion (2002) and Champion and Cassidy (2002a). Geochronology references are in the text**

### Jaguar

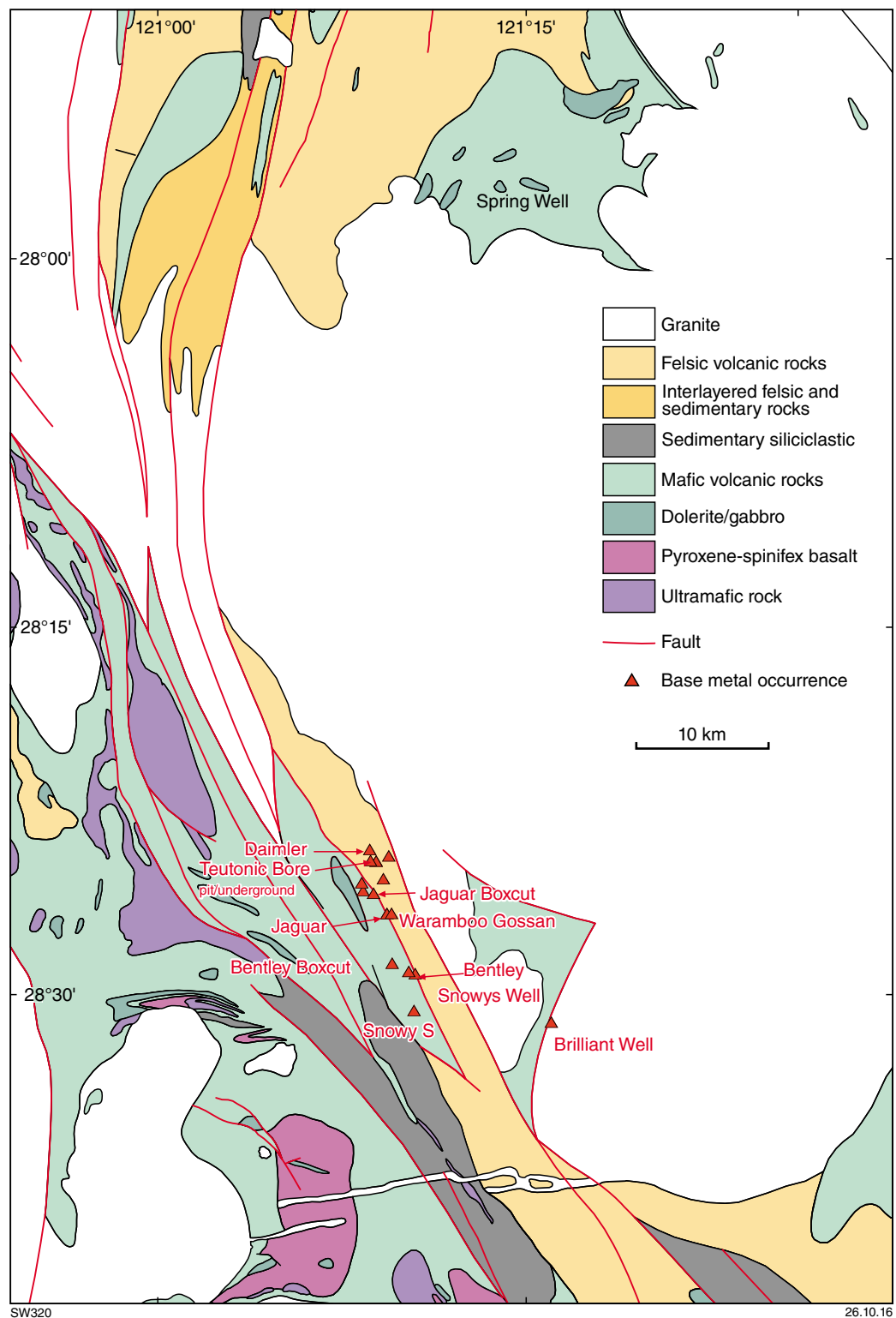
The Jaguar VMS deposit (1.60 Mt pre-mining reserve at 11.3% Zn, 3.1% Cu, 115 g/t Ag) was discovered in 2002, about four kilometres south of Teutonic Bore (Fig. 19), in the second hole of a diamond-drilling program designed to follow up on a regional Crone 'Deep EM' anomaly (Ellis, 2004). The geophysical anomaly which led to the discovery of the deposit is located immediately west of the Warramboos gossan, which had been drilled in 1984, returning 5.9 m at 2.2% Zn 0.4% Pb, 58 g/t Ag. Both diamond drillholes that tested the conductor resulted in anomalous base metal mineralization. The second hole intersected 7.7 m of massive sulfide at 4.3% Cu, 16.1% Zn, 0.8% Pb, 173 g/t Ag and 0.24 g/t Au (Ellis, 2004).

The mine stratigraphy at Jaguar has been described in detail by Belford (2010; also see Belford et al., 2015), and is summarized below (Fig. 20). The footwall sequence has been divided into the Deep Footwall Andesite, Footwall Rhyolite (calc-alkaline), Footwall Andesite (transitional)

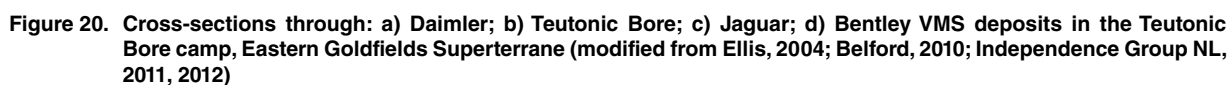
and Footwall Basalt (tholeiitic). The Mineralized Package (Belford, 2010; Belford et al., 2015) includes dacite (both tholeiitic and calc-alkaline varieties), two distinct pumice-rich facies, conglomerate and a laminated sedimentary facies (including volcanic mudstone, volcanic sandstone, conglomerate, thin beds of chert and mudstone/black shale). The hangingwall sequence was divided into the Hangingwall Andesite (calc-alkaline), Hangingwall Basalt (tholeiitic), Upper Porphyritic Andesite (strongly calc-alkaline) and two sedimentary units. Mafic doleritic sills intrude the host stratigraphy (Fig. 20) and are geochemically similar to basalts in the hangingwall (Belford, 2010).

As the Jaguar orebody has been intruded by several dolerite sills, it has been divided into a number of lenses. The 'Main Zone' of massive sulfide mineralization is a continuous, dipping sheet that extends 315 m along strike, 375 m down dip and has an average thickness of 4.35 m (Ellis, 2004). 'Footwall lenses' are chalcopyrite-rich and sphalerite-poor compared to the 'Main Zone' (Ellis, 2004).





**Figure 19. Simplified regional geology of the Teutonic Bore volcanic complex in the Eastern Goldfields Superterrane. Geology is based on GSWA (2014a); mineral occurrences are from GSWA (2015b)**



Upper contacts to mineralization are typically sharp. Footwall contacts are gradational into stringer mineralization, unless intruded by dolerite. The dominant sulfide minerals in the deposit are pyrite, pyrrhotite, sphalerite and chalcopyrite (and locally, magnetite). Galena and arsenopyrite are present as minor phases, and trace amounts of tetrahedrite–tennantite and geochronite were identified by Belford (2010). Hydrothermal alteration is confined to the immediate vicinity of lenses and footwall stockwork or feeder zones with a maximum distance of about 20 m into mafic footwall rocks. Footwall alteration is dominated by chlorite, epidote, pyrite and calcite, with locally developed silicification, albite and sericite (Ellis, 2004). See Belford (2010; also Belford et al., 2015) for further detail on the Jaguar deposit.

### Bentley

The Bentley VMS deposit, about 4 km south of Jaguar (Fig. 19) was discovered in 2008 during a systematic diamond drilling campaign designed to test a near-surface geochemical anomaly, known as the Snowy's Well prospect (Independence Group, 2011). The deposit was brought into production in June 2011 when the decline development intersected the top of the orebody (Independence Group, 2011). Similar to the Teutonic Bore and Jaguar deposits, the Bentley deposit occurs at or near the base of a mafic–intermediate volcanic succession (which includes sedimentary horizons) overlying a felsic volcanic and volcanoclastic package (Jabiru Metals Ltd, 2010; Fig. 20). Mineralization consists of a series of Cu–Zn–Pb–Au–Ag-rich massive sulfide lenses and has been split by dolerite sills. At Bentley, additional lenses continued to be discovered by deep drilling to ~1000 m below surface by the end of 2015.

Regional exploration along strike to the northwest and southeast has also identified numerous VMS targets through a combination of ground-based geophysics, regolith geochemistry and detailed geological mapping (Independence Group, 2011). Other targets include Lagonda, Triumph, Daimler (Fig. 20), Teutonic Bore South, and Bentley South (see Independence Group, 2012 and subsequent annual reports). A detailed multi-sulfur isotope study of the Teutonic Bore, Jaguar and Bentley deposits was recently presented by Chen et al. (2015).

### Nimbus Deposit

The Nimbus Ag–Zn–(Au) deposit is located approximately 265 km south of Teutonic Bore and 17 km east-southeast of Kalgoorlie (Fig. 1b). Initially discovered in 1995, the deposit lies in the uppermost felsic rocks of the Boorara Domain (Cassidy et al., 2006) of the Kalgoorlie Terrane (c. 2680 Ma). Its origin has been debated, with previous workers either favouring a fault-controlled high-sulfidation system (Henderson et al., 2012) or seafloor to sub-seafloor VMS mineralization (Hadlow et al., 2011; Belford, 2011). Primary sulfide resources form a series of stacked, steeply plunging lenses (Fig. 21) that overlie mined supergene and oxide mineralization. Between 2004 and 2006, deeply weathered oxide and supergene ('transition') material was mined by Polymetals WA from two small open pits (Discovery and East) for a total production of 0.319 Mt

at 352 g/t Ag (Henderson et al., 2012). In May 2016, the global Nimbus resource comprised 12.1 Mt at 52 g/t Ag, 0.9% Zn and 0.2 g/t Au (MacPhersons Resources Ltd, 2016).

The following account is after Hollis et al. (in press). Although hydrothermal alteration, tectonic deformation and deep weathering obscure much of the primary mineralogy at Nimbus, remnant volcanic textures are well preserved in diamond drillcore and in saprolite in the Discovery and East pit walls. Mineralization is present in a northwesterly (to north-northwesterly) trending and steeply dipping bimodal package of volcanic rocks (quartz–feldspar–phyric dacite and lesser basalt, plus their autoclastic equivalents) with subordinate black carbonaceous mudstone, chert, tuff, polymict conglomerates and volcanic breccias. The stratigraphy is dominated by rocks of dacitic composition. All rocks described here have been subjected to lower greenschist facies metamorphism.

In the primary sulfide zone, early, well-developed massive pyrite is underlain by: 1) semi-massive, stringer and breccia-type Ag–Zn ± Pb (± rare Cu–Au) sulfides (including pyrite, low- and high-Fe sphalerite, galena, pyrrhotite, marriite, boulangerite, arsenopyrite, chalcopyrite, Ag-bearing tetrahedrite, electrum and amalgam) associated with the autoclastic facies of thick units of dacite; and 2) stringer and disseminated sulfides (dominated by pyrite and sphalerite) in coherent pseudo-brecciated dacite. Hydrothermal alteration in dacite is characterized by intense and pervasive quartz–sericite–carbonate ± fuchsite. Compared to other VMS occurrences in the Yilgarn Craton, the Nimbus deposit is unusual in terms of its tectono-stratigraphic position, the geochemistry of its host sequence (i.e. FI-affinity felsic volcanic rocks, ocean plateau-like low-Th basalts), mineralogy (e.g. low Cu, abundance of Sb sulfosalts, high Ag and Hg), and carbonate–sericite-dominated alteration assemblages. Classification of Nimbus as a shallow-water and low-temperature VMS deposit with epithermal characteristics (i.e. a hybrid bimodal–felsic deposit) is consistent with its position near the margin of the Kalgoorlie/Kurnalpi terrane boundary (Fig. 2).

### Anaconda occurrences

Base metal mineralization in the Anaconda (Murrin Murrin) area (Fig. 18) lies approximately 45 km east of Leonora. Historic copper production, mainly prior to 1908, was from supergene mineralization above small copper–zinc sulfide lenses hosted in a series of epiclastic shales and lithic wackes (Marston, 1979). Historically, three copper–zinc deposits were recognized (Fig. 22): the Anaconda (Eulaminna, Mount Malcolm) mine, the Nangeroo (Butte City) mine, and the Rio Tinto workings (Marston, 1979). Approximately 94% of total copper produced (4595 t) was from the Anaconda mine.

Mineralization occurs at two stratigraphic levels, which are towards the top of a 600 m thick succession of fine- to coarse-grained and rudaceous, poorly sorted, volcanoclastic and sedimentary rocks, carbonaceous shale, rhyolite, dacite and minor mafic volcanic rocks (Marston,

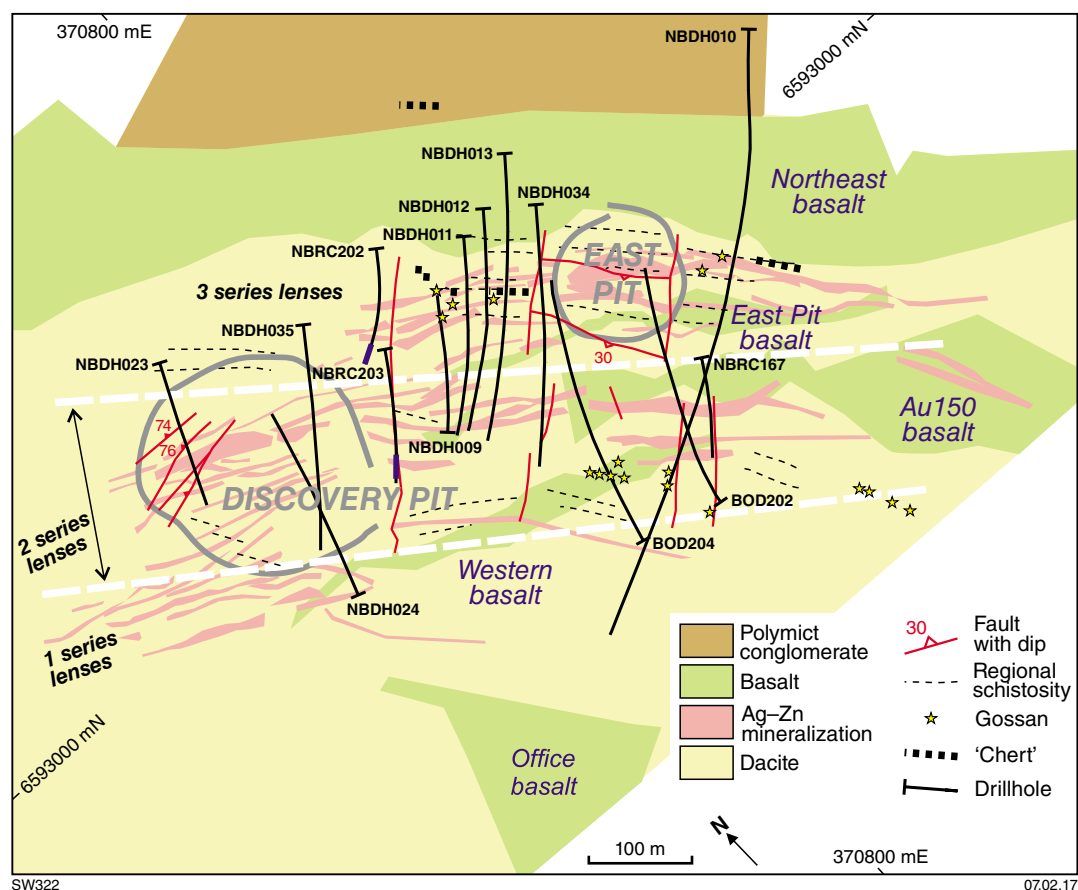


Figure 21. Simplified regional geology of the Nimbus mine area after Majoribanks (2012)

1979). This succession is overlain by pillowed tholeiitic basalt and intruded by dunitic and gabbroic sills (Murrin Murrin Igneous Complex). The Anaconda deposit lies on the western limb of the Kilkenny Syncline, and the Nangeroo deposit, six kilometres to the northeast, is at a similar stratigraphic level on the eastern limb (Fig. 22). The Kilkenny Syncline, which is repeated to the west by the Lamb Fault, hosts the Rio Tinto deposit, about five kilometres north of Anaconda. This deposit sits slightly higher in the sequence and is hosted in a thin felsic tuff unit interbedded with tholeiitic and komatiitic basalt. Felsic tuff from one kilometre south of the Anaconda copper mine, where it is interbedded with spinifex-textured komatiitic flows, has yielded a U–Pb zircon age of  $2698 \pm 5$  Ma (GSWA 127238, Nelson, 2005).

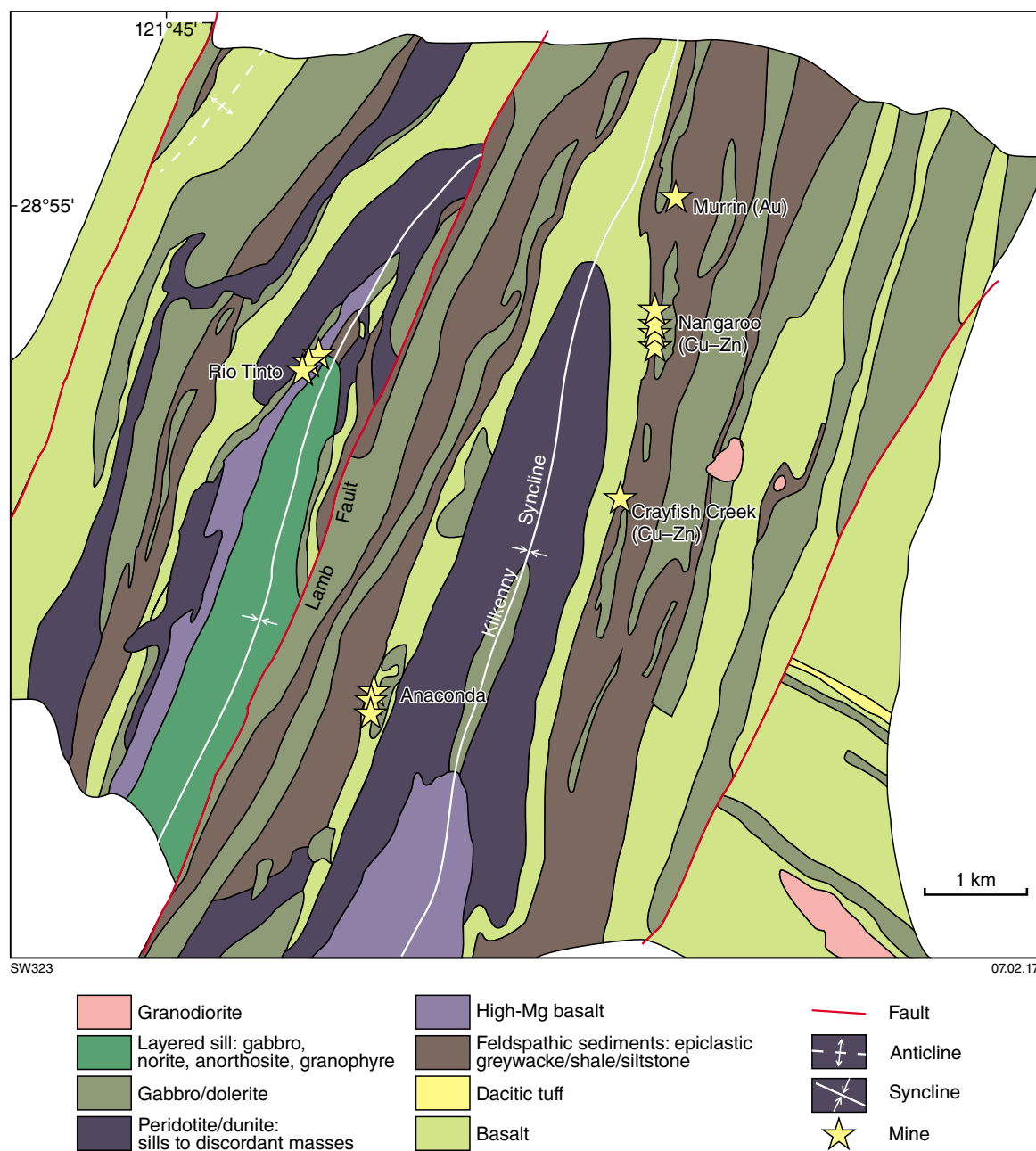
Sulfide mineralization at Anaconda occurs predominantly as lenses of massive pyrite, with lesser sphalerite and chalcopyrite. Some of the lenses show asymmetric zonation, with layered copper–zinc sulfides underlain by a sulfide-bearing chlorite–carbonate alteration zone. Further detail on the deposits is presented in Marston (1979). Exploration activity is summarized in Kumarina Resources (2012). The majority of regional and prospect drill testing has been to shallow depths only. The Nangeroo, Crayfish Creek and Rio Tinto base metal occurrences remain open at depth and have not been fully tested by recent advanced geophysical techniques (Kumarina Resources Ltd, 2012).

### Erayinia (King) occurrence

In the southern Kurnalpi Terrane, VMS mineralization has been identified at the King deposit (Erayinia area), about 150 km southeast of Kalgoorlie, east of the Claypan Fault (Fig. 23). Massive sulfide mineralization at King (previously known as Calliope; see Jones, 2007) was intersected after testing an EM target in 2002. Reverse-circulation drillhole EC8 intersected 4 m of mineralization at 1.34 % Zn within a pyrite–pyrrhotite zone (GSWA, 2015b, site S0029712).

The local stratigraphy (overturned) comprises chloritic schist and garnet-bearing amphibolite in the deep footwall, and intermediate to dacitic volcanic/volcaniclastic rocks in the immediate footwall (Hollis et al., 2016b). Mineralization occurs near the contact between felsic volcanic rocks and a layered magnetite-bearing chert, which may be an exhalite (Tantalum Australia, 2005; Rees, 2008). A chloritic feeder zone in the garnet-bearing amphibolite is characterized by abundant magnetite–pyrrhotite with lesser pyrite–chalcopyrite. Quartz–sericite alteration surrounds massive sulfide intervals in felsic rocks, and contains abundant recrystallized stringers of pyrite with minor sphalerite.

A U–Pb zircon age of  $2680 \pm 5$  Ma has been obtained for a rock four kilometres along strike of the King occurrence



**Figure 22. Regional geology and base metal occurrences of the Anaconda area, Eastern Goldfields Superterrane (after Ferguson, 1999)**

(Wingate and Bodorkos, 2007b). Numerous Zn prospects along strike to the north and south are associated with EM anomalies. Drilling west of the Claypan Fault (diamond drillholes EC154D to EC158D in Fig. 23) has identified VMS proximal hydrothermal signatures and low level Zn mineralization. Intercepts of massive pyrite may be significant (James, 2015).

## Jungle Pool occurrence

The Jungle Pool base metal occurrence (Fig. 18) lies approximately 120 km south of the Teutonic Bore camp and about 60 km southwest of Anaconda. In April 2011, reverse circulation (RC) drilling by White Cliff Nickel Ltd intersected wide zones of iron-rich massive sulfides within altered mafic volcanic rocks. Analysis revealed only two weakly anomalous base metal zones of 4 m at 0.1% Cu at the oxide – massive sulfide interface (at about 80 m depth) and 4 m at 0.15% Zn within fresh sulfides (at about 104 m depth). A silica cap was identified over massive sulfides and weak quartz–sulfide stringer alteration zone in the footwall of the deposit (White Cliff Nickel Ltd., 2011). There are no U–Pb age constraints for the immediate host succession. U–Pb zircon geochronology from felsic volcanic rocks in the contiguous Melita Formation (Wyche et al., 2016) to the north yielded ages of c. 2683 Ma (Brown et al., 2002; Nelson, 1997c) and may constrain the age of VMS mineralization at Jungle Pool.

## Balagundi

Pioneer Resources have recently explored for VMS mineralization around Balagundi in the southern Gindalbie Domain (Cassidy et al., 2006), northeast of Nimbus (Fig. 1b). Exploration activity has included detailed regolith and geological interpretations, field mapping, RAB and RC drilling, geochemical, and PIMA analysis (McIntyre, 2014). A number of geochemical targets and alteration zones have been identified. The most significant mineralization lies within the Red Bluff Gully horizon, which consists of a thin (100–200 m) package of shale, volcanoclastic sedimentary rocks, including conglomerates, and felsic volcanic rocks, underlain by pillowed basalt and overlain by mafic volcanic rocks and dolerite (McIntyre, 2014).

## Brilliant Well

The Brilliant Well copper–zinc base metal occurrence is located approximately 40 km north of Leonora and 10 km southeast of Bentley in the Kurnalpi Terrane (Fig. 19). An anomalous zone of copper was intersected in drillholes BWRC053, BWRC054 and BWRC055 in weathered mafic volcanic rocks near the Deep Well Shear Zone. The best intersection was in RC drillhole BWRC055, which returned 11 m at 1356 ppm Cu and 222 ppm Zn (Rohde, 2015). High gold values associated with quartz veins were also reported from rock chip drilling farther north. Alteration zones in the Deep Well shear zone are characterized by sericite, quartz veining and minor oxidized sulfide (Rohde, 2015).

## Duketon occurrences

In the Duketon greenstone belt, VMS prospects occur in a sequence of epiclastic sedimentary rocks within a rhyolite–andesite sequence at Tuff Hill, Mason Hill and Fisher Well (Figs 1b, 2). Styles of mineralization and exploration activity for the three areas have been described by Ferguson (1999), summarized below.

At Tuff Hill, five kilometres west-southwest of Duketon, disseminated sulfides were initially recognized in quartz–sericite schist during exploration by CEC and Esso Exploration (1973–1988). Percussion drilling identified zinc-dominant disseminated and massive sulfides in pyroclastic rocks, and subsequent diamond drilling intersected narrow zones of massive sulfides (<30 cm thick). The best result at Tuff Hill was 0.8 m at 2.9% Zn, 1.3% Pb, 0.26% Cu and 70 g/t Ag (Ferguson, 1999). Hydrothermal alteration associated with mineralization is characterized by sericite, silica, carbonate and chlorite.

Approximately seven kilometres west-northwest of Duketon at Mason Hill, anomalous base metal values were identified by CEC in a mixed volcanic–sedimentary sequence including rhyolite–andesite flows, tuff and breccias with minor chert, and mafic and sedimentary rocks (Ferguson, 1999). Enrichments of cobalt, bismuth and gold in gossans led to subsequent percussion and diamond drilling. Narrow, high-grade zones of crudely layered sphalerite–galena–pyrite with minor chalcopyrite and tennantite were identified in rhyolite breccia (e.g. 0.3 m at 9.3% Zn, 1.5% Pb, 0.07% Cu and 57 g/t Ag; Ferguson, 1999).

The Fisher Well base metal occurrence, 8.5 km south of Duketon, occurs in the southerly extension of the sequence exposed around Tuff Hill and Mason Hill (Ferguson, 1999). Percussion drilling, followed by RAB drilling, encountered disseminated and vein pyrite, sphalerite, subordinate galena and minor chalcopyrite in tuffs and agglomerates (e.g. 0.3 m at 1.2% Cu). Hydrothermal alteration is characterized by silica, sericite and tourmaline as at Mason Hill.

## South West Terrane

### Wheatley

The Wheatley VMS prospect (Fig. 1b) lies in the Balingup metamorphic belt, a deformed and metamorphosed complex comprising turbiditic metasedimentary rocks and orthogneiss (Wilde, 2001). The Wheatley joint venture between Teck Cominco and BHP Billiton discovered the Kingsley VMS prospect in 2004. Further work by an expanded joint venture revealed sulfide mineralization to be hosted at a transition between quartz–feldspar–biotite gneiss and amphibole–biotite–feldspar amphibolites, marking a change from felsic to mafic volcanism (Yeats, 2007). The footwall to the mineralization is characterized by Na-depleted quartz–garnet–biotite–sillimanite–staurolite schists, which are considered to represent a metamorphosed hydrothermal assemblage (Yeats, 2007).



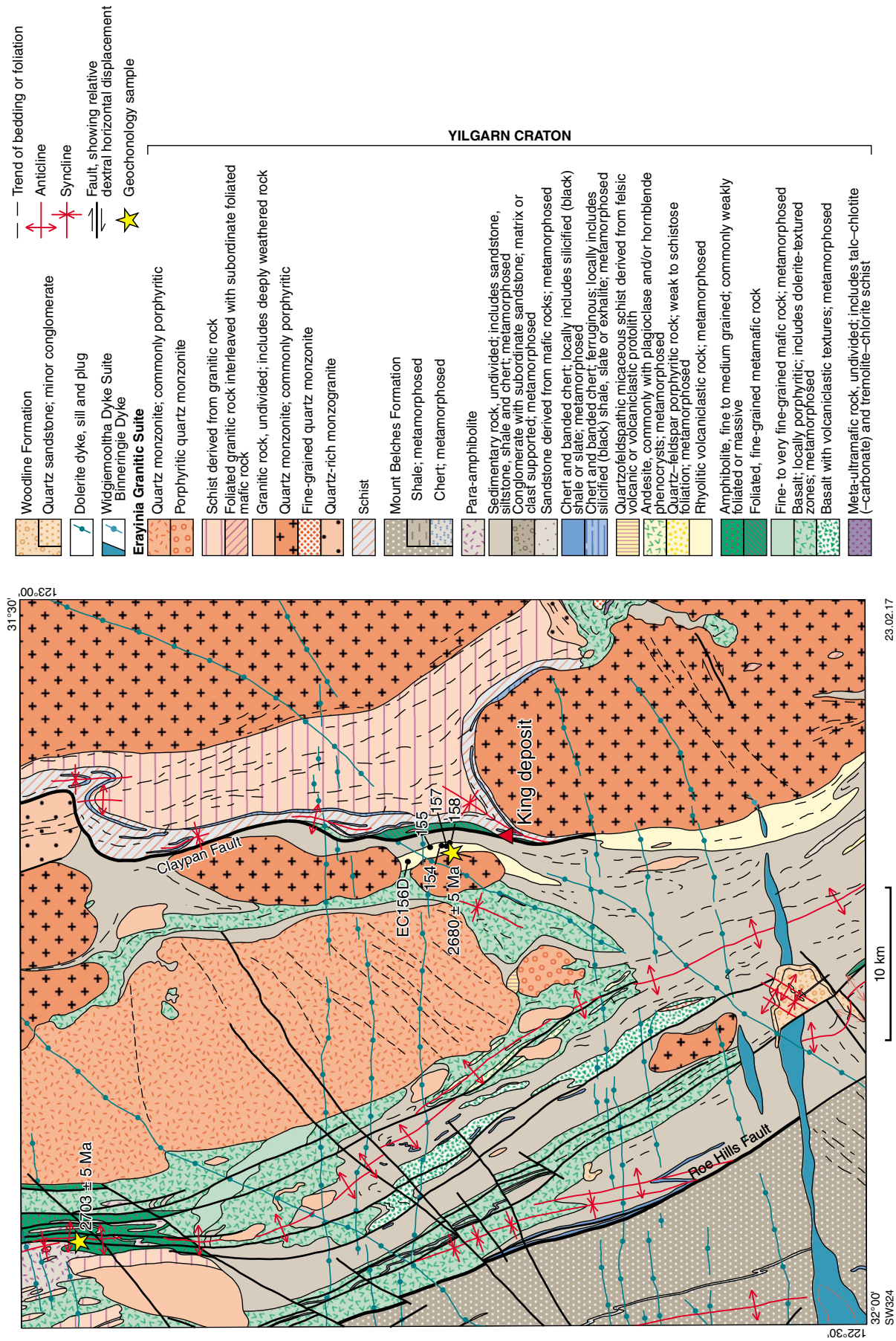


Figure 23. Regional geology of the Eraynia area showing the positions of diamond drillholes from James (2015) and the location of the King VMS deposit (modified from Jones, 2007)

Mineralization is dominated by pyrrhotite with lesser pyrite, minor arsenopyrite, galena and sphalerite. The best result from drilling was an intersection of 4.1 m at 2.2% Zn (Hampton Hill Mining NL, 2016). U–Pb zircon geochronology on a ‘psammite’ in the footwall of minor Zn–Cu mineralization in drillhole WPD02 (GA sample ID 2004968001A) yielded a maximum depositional age of c. 646 Ma, with a spread of ages from c. 2700 to 2600 Ma (Sircombe et al., 2007). The significance of these dates is not clear.

## Wongan Hills and Calingiri

In the northern South West Terrane, the Wongan Hills greenstone belt (Fig. 1b) comprises metamorphosed mafic and felsic volcanic rocks, chert, banded iron-formation and subordinate schist, gneiss and small ultramafic intrusions (Pidgeon and Wilde, 1990a). At the Mystery VMS prospect, a multi-element geochemical anomaly of zinc–lead–copper–gold–arsenic–tin–indium–bismuth–antimony lies close to a major contact between a succession of felsic footwall volcanic rocks, and a hangingwall succession of mafic and sedimentary rocks. Farther to the southwest, this horizon hosts bedrock lead–zinc–silver mineralization at the West Wongan Target (e.g. 3 m at 0.29% Pb, 0.11% Zn, 39.4 g/t Ag) near a major shear zone (Sutherland, 2013). SHRIMP U–Pb zircon geochronology by Pidgeon and Wilde (1990a) from a porphyritic felsic rock in the northernmost, mafic-dominated part of the Wongan Hills greenstone belt yielded an age of  $3010 \pm 7$  Ma. Younger U–Pb titanite ages near the Wongan (and Ninan) base metal occurrences (c. 2646 Ma) record metamorphism (Pidgeon and Wilde, 1990a).

## Narryer Terrane

No significant VMS occurrences have been reported in the Narryer Terrane. This is most likely due to lack of Archean supracrustal lithologies, extensive Proterozoic deformation and minimal historic exploration.

## Prospectivity of the Yilgarn Craton

This section is adapted from Hollis et al. (2015), which reviewed the main geochemical associations of VMS deposits in the Yilgarn Craton. Here we detail the geochemistry of felsic and intermediate volcanic rocks from localities across the Yilgarn Craton to identify additional areas that may be prospective for mineralization.

## What is geochemically prospective?

Recent advances in the understanding of VMS deposit formation and their common petrochemical associations have provided an opportunity to re-examine VMS prospectivity across the Yilgarn Craton. Investigation into why some terranes are devoid of VMS mineralization, whilst others are VMS rich has been the subject of

substantial historical research (Leshner et al., 1986; Lentz, 1998; Wyman, 2000; Piercey et al., 2001; Hart et al., 2004; Piercey, 2011).

VMS deposits throughout the geological record form within volcanic successions due to focused heat flow associated with hydrothermal convection (e.g. Galley, 1993, 2003; Franklin et al., 2005; Galley et al., 2007). The geochemical composition of felsic volcanic suites have been used to distinguish VMS-prospective from VMS-barren systems (e.g. Leshner et al., 1986; Barrie et al., 1993; Barrett and MacLean, 1999; Lentz, 1998; Piercey et al., 2001; Hart, 2004). Leshner et al. (1986) first outlined a threefold division of specifically Archean VMS-fertile versus barren felsic rocks from the Superior Province of Canada (FI to FIII) with FII–FIII being considered the most fertile. This scheme was subsequently modified by Hart et al. (2004) to include a fourth type (FIV) of rhyolites common to post-Archean primitive arc sequences (reviewed in Piercey, 2011).

- FI rhyolites are typically calc-alkaline (high Zr/Y, La/Yb, Th/Yb) with relatively low HFSE contents and strongly light rare earth element (LREE) enriched chondrite-normalized REE profiles relative to the heavy rare earth element (HREE). This petrochemically unfavourable suite is indicative of deep melting and reduced crustal heat flux. Strong depletion of the HREE over LREE (i.e. high La/Yb, low Yb) indicates the residence of garnet in the source region.
- FII represents an intermediate stage between FI and FIII. In post-Archean evolved VMS settings, felsic rocks of this type are typically HFSE and REE enriched, have within-plate (A-type) characteristics, and are calc-alkaline to peralkaline in composition.
- FIII rhyolites are characterized by low Zr/Y and La/Yb, elevated  $\text{SiO}_2$ , flat and tholeiitic chondrite-normalized REE patterns, and elevated HFSE contents (especially Y, Zr >200 ppm). These rocks are interpreted to have formed within rift sequences from high-temperature melts ( $T > 900^\circ\text{C}$ ) derived from the melting of hydrated tholeiitic basaltic crust at shallow to mid-crustal depths during extension. 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. FIII rhyolites are subdivided into FIIIa types with typically moderately negative Eu anomalies, low Zr/Y and high Sc and intermediate abundance of HFSE, and FIIIb types with pronounced negative Eu anomalies, low Zr/Y high HFSE abundance and low Sc and Sr.

FIV rhyolites are most abundant in primitive post-Archean arcs. These felsic rocks have tholeiitic to boninite-like affinities and are characterized by low Zr/Y, flat REE profiles and primitive-mantle normalized patterns with negative Nb anomalies and HFSE depletion (Zr <50–100 pm). ‘Boninitic rhyolites’ are similar but have classic U-shaped REE profiles similar to true boninites, and have been attributed to the melting of mafic (to andesitic) substrates commonly associated with forearc rifting, intra-arc rifting, or rifting during the initiation of back-arc basin activity.

## Methods

To investigate the VMS prospectivity of felsic rocks across the Yilgarn Craton, whole-rock geochemical data was compiled from a variety of published and unpublished sources (detailed in Hollis et al., 2015 and below). The aim was twofold: first, to characterize the geochemistry of felsic rocks associated with VMS deposits in the Yilgarn (as described in Hollis et al., 2015); and second, to subsequently identify areas that contain geochemically identical felsic rocks that are prospective for mineralization (detailed here). The dataset was adapted from the following sources: Frost (1992); Whitford and Ashley (1992); Morris and Witt (1997); Yeats and Groves (1998); Hill et al. (1999); Messenger (2000); Sharpe and Gemmell (2001); Brown et al. (2002); Barley et al. (2002, 2008); Vickery (2004); Belford (2010); Barnes et al. (2012); Wyman and Kerrich (2012); Duuring and Hagemann (2013); Van Kranendonk et al. (2013); GSWA (2014b); Belford et al. (2015).

In the first instance, all samples were divided into lithological groupings based on available rock descriptions. Samples of granite–gneiss, banded iron-formation, and sedimentary rocks were removed from the database. All samples that lacked rock descriptions were also removed. As the datasets included were produced using various techniques, over several decades and 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. La, Th, Nb, Ta, and Hf). To overcome this problem, all data below 1.5x typical XRF trace element detection limits were excluded to maintain a high degree of quality in the retained database (Table 2). ICP-MS data less than 1.5x XRF detection limits were also removed as these datasets were also produced over a number of decades and analysis by ICP-MS itself is not a measure of quality. Incomplete digestion techniques will produce artificially low values of a number of key elements in coarse-grained and intermediate to felsic rocks (e.g. Zr, Y, Nb, HREE) if high-pressure dissolution or sinter techniques were not used. This is particularly true for older datasets and ‘company data’.

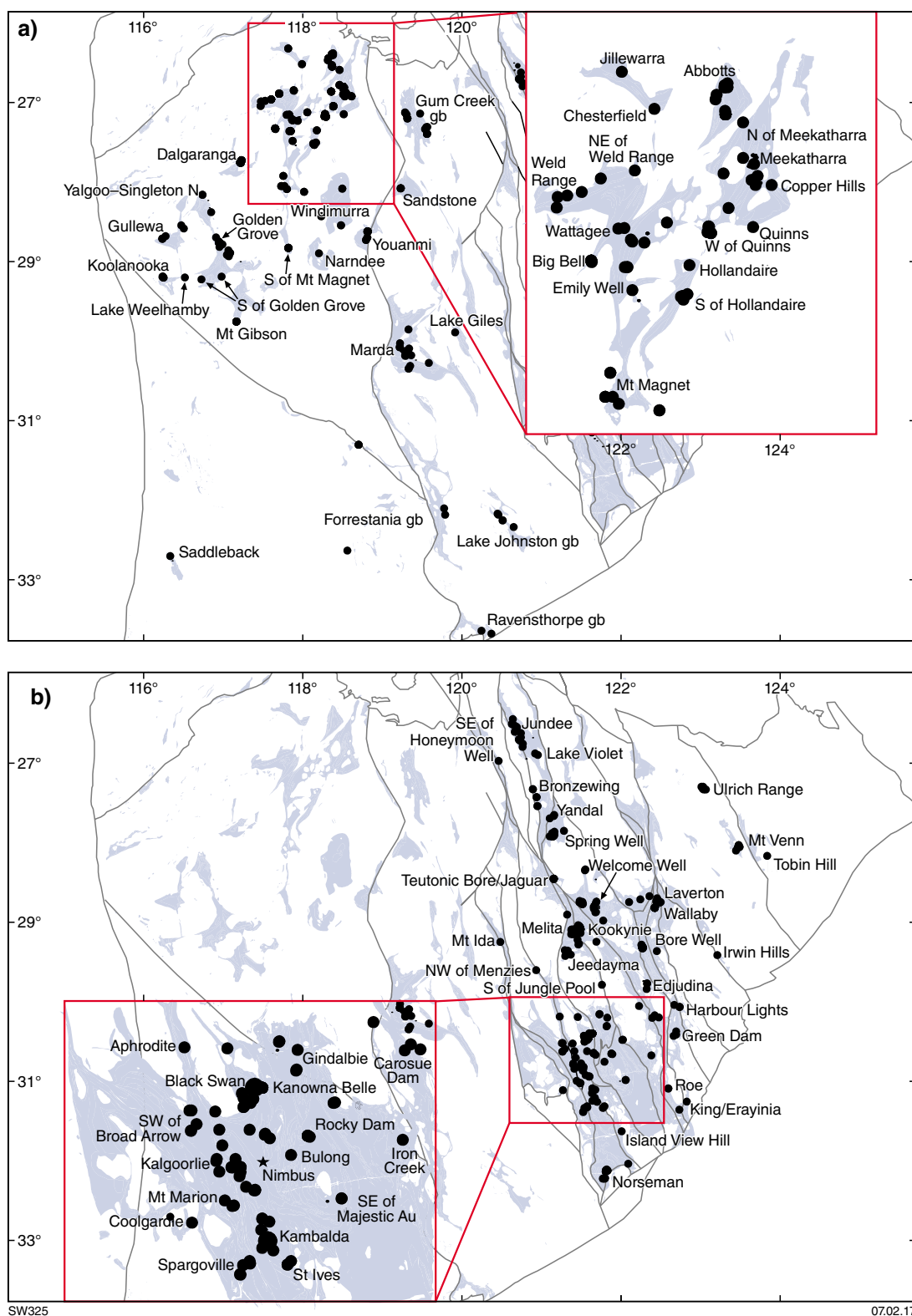
The only exception for the above 1.5x rule was for the REE, which were retained if the analysis included the HREE and was obtained by ICP-MS in recent years (e.g. Van Kranendonk et al., 2013) or displayed relatively smooth REE profiles. Tantalum and Hf data were also retained, although no ratios were calculated using these elements. Cutoff values predominantly affected ultramafic and mafic rocks, which are not of interest here. Major element data were recalculated to 100% excluding LOI, S, CO<sub>2</sub> and H<sub>2</sub>O<sup>+</sup>. Trace elements were recalculated using the same corrections to maintain immobile-element ratios. Fe is reported as Fe<sub>2</sub>O<sub>3</sub>T calculated from FeO and Fe<sub>2</sub>O<sub>3</sub> values after Grunsky et al. (2013). All sample locations are shown in Figure 24. Samples from the northern Murchison Domain are shown in the context of the stratigraphy of Van Kranendonk et al. (2013) in Figure 25.

**Table 2. Cutoff values used in this Report**

Element(s)	Cutoff value
Ag, As, Bi, Li, Mo, Rb, Sb, Sn, Sr, Th, U, W	1.5 ppm
Cu, Cr, Ga, Nb, Ni, Y, Zn, Zr, Sc	3 ppm
Pb	4.5 ppm
La, Ce	6 ppm
Co, V	7.5 ppm
Ba	15 ppm

Following the subdivision of samples into lithology groupings based on rock descriptions and the removal of questionable low-level data, samples were chemically classified using a number of standard published diagrams (Fig. 26). This was primarily to check if samples had been correctly named in the first instance. Ideally, volcanic rocks should be classified according to a TAS diagram, if not by thin section. However, as discussed previously, extensive hydrothermal alteration is common across the Yilgarn Craton and the use of SiO<sub>2</sub> for classification purposes should be avoided. This is demonstrated in Figure 26a, where a number of intermediate rocks plot at much higher SiO<sub>2</sub> values, well into the andesite and dacite fields. This was also the case for mafic rocks (not shown). Large mass gains of SiO<sub>2</sub> are not always apparent in analytical data due to the effects of closure. A more appropriate method for classifying altered volcanic rocks is to use the immobile element ratios Zr/TiO<sub>2</sub> and Nb/Y. Protolith compositions can be determined using the diagrams of Winchester and Floyd (1977) and Pearce (1996) as indicated in Figure 26b,c. Although these diagrams should ideally not be used for rocks which may contain xenocrystic zircons, they provide a relatively robust method for discriminating most samples. Classifications using bivariate plots which do not use immobile element ratios are not suitable for hydrothermally altered rocks. One such example is the Th–Co classification scheme of Hastie et al. (2007). Although thorium is immobile, cobalt can be significantly enriched around mineralized zones and the concentrations of both elements can be affected by mass change. From comparison between rock descriptions and the Pearce (1996) diagram (Fig. 26b,c), it is clear a large number of rocks classified as ‘felsic’ display intermediate Zr/TiO<sub>2</sub> ratios. A number of ‘mafic’ rocks also display intermediate Zr/TiO<sub>2</sub> ratios. There are three possible reasons for this:

1. Zircon inheritance is a common feature of most felsic and intrusive rocks of the Yilgarn Craton. Any inherited zircons present will result in uncharacteristically high whole-rock Zr/TiO<sub>2</sub> ratios.
2. The samples may not have been correctly named. This is a common problem in hydrothermally altered volcanic terrains, especially for units that are poorly exposed or not examined in thin section. Bleached and silicified volcanic rocks are commonly described as ‘felsic’ in the field, and darker, commonly chloritized or pillowed, flows as ‘mafic’.



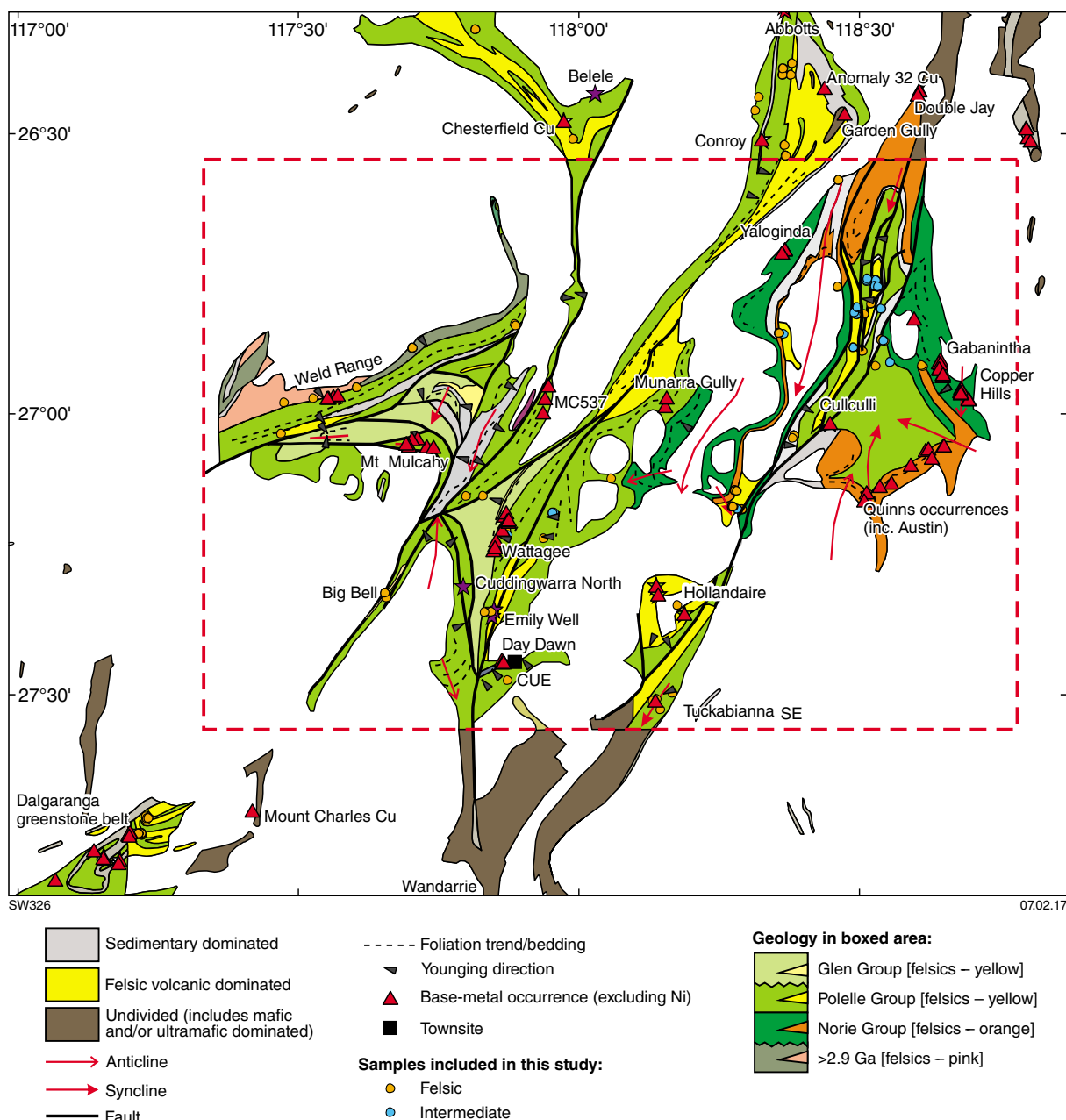
**Figure 24. Sample localities of felsic and intermediate rocks included in this study from: a) the Youanmi and South West Terranes; b) the Eastern Goldfields Superterrane; gb, greenstone belt**



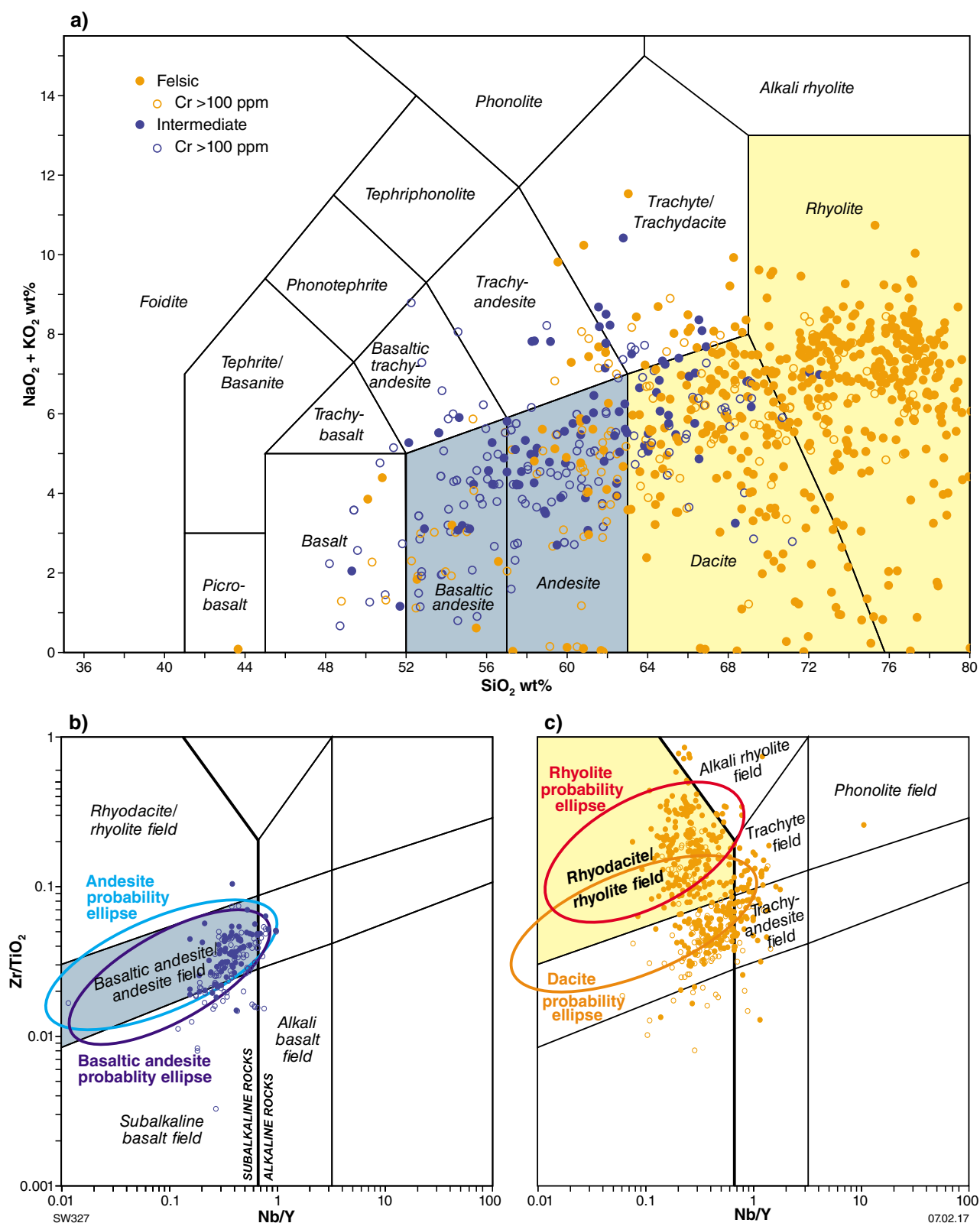
Many of the rock descriptions for the samples included here were brief: some were simply called ‘mafic volcanic’ with no additional information. Belford (2010) documented the significance of andesites in the Jaguar stratigraphy, in an area of the Gindalbie Domain (Cassidy et al., 2006) frequently referred to as bimodal in the literature. Andesites also form an important part of the Golden Grove stratigraphy and thus occur in both major VMS camps of the Yilgarn Craton. They have also recently been noted at Hollandaire (Hayman et al., 2015) and King (Hollis et al., 2016b).

3. The data fall within the ‘noise’ of the classification diagram. The original Winchester and Floyd (1977)  $Zr/TiO_2$  vs  $Nb/Y$  diagram was published at a

time when few high-quality trace-element data were available. Pearce (1996) revised the original boundaries of this diagram using approximately 8000 data points. However, 10% probability contours still showed significant overlap between the major fields (Fig. 26b,c). Although the revised diagram still allowed basic, intermediate and evolved rocks to be distinguished to some degree, it was also noted that some syncollisional and volcanic-arc basalts classify as intermediate compositions because their mantle sources are modified by subduction melts with high  $Zr/TiO_2$  ratios. Pearce (1996) suggested that lavas that plot in the intermediate field should be classified as basic if they contain  $Cr > 100$  ppm, as  $Cr$  is strongly compatible in mantle phases, thus indicative of primitive rather than intermediate magmas.



**Figure 25. Sample localities from the northern Murchison Domain, Youanmi Terrane, plotted relative to the regional stratigraphy of Van Kranendonk et al. (2013) and base metal occurrences**



**Figure 26. Whole-rock geochemistry classified by sample description: a) total alkali – silica (TAS) diagram for intermediate and felsic rocks; b), c) Yilgarn volcanic rocks classified by rock descriptions on the immobile element classification diagram of Pearce (1996). Probability ellipses of Pearce (1996) for various rock types are shown. These ellipses represent 10% probability contours; that is, 10% of samples from that group will plot outside the respective contour. Open symbols represent samples with Cr > 100 ppm**



To resolve these inconsistencies, data were plotted with the probability ellipses of Pearce (1996) as shown in Figure 26b,c. Although most rocks described as intermediate plot in the andesite and basaltic andesite ellipses, a number of samples described as felsic and mafic sit outside their respective ellipses at intermediate Zr/TiO<sub>2</sub> values. These ‘mafic’ rocks include both low-Cr and high-Cr (>100 ppm) varieties. The former most likely represent andesites and the latter either mafic rocks that contain inherited zircons or magmas related to subduction-zone processes. Samples described as felsic that fall outside the Pearce (1996) rhyolite and dacite ellipses display low Zr/TiO<sub>2</sub> and high Cr, again suggesting that some of these rocks may be intermediate in composition. A large number rocks described as felsic, and which contain Cr <100ppm, also plot in the intermediate Zr/TiO<sub>2</sub> field but within the dacite ellipse. As no geochemical parameters could be identified to adequately classify the data according to their rock descriptions (including SiO<sub>2</sub>, MgO, Cr and immobile ratios), it is likely that a number of samples have been incorrectly named. As the principal goal of this work is to identify petrochemically prospective felsic sequences in the Yilgarn Craton, and in the context of the limitations noted above, all rocks described as intermediate were retained as such.

In addition to classification by rock descriptions, samples were also classified according their geochemical characteristics. Despite problems discussed above in applying the Pearce (1996) scheme to the Yilgarn dataset, it still provides the most reliable way of determining protolith compositions for hydrothermally altered volcanic rocks subjected to mass change. No suitable alternative differentiation index to Zr/TiO<sub>2</sub> was identified. MgO and SiO<sub>2</sub> show some degree of correlation to Zr/TiO<sub>2</sub>, but cannot be considered reliable, especially for hydrothermally altered rocks. La/V and Th/V also show strong correlations to Zr/TiO<sub>2</sub>. However, the use of both would misclassify felsic rocks of tholeiitic affinity, which are characterized by high zirconium and low lanthanum and thorium. Ratios using Al<sub>2</sub>O<sub>3</sub>, cobalt, chromium, ytterbium, tantalum and yttrium generated considerable overlap and scatter between different rock types. Although the Winchester and Floyd (1977) diagram provides more fields for discrimination purposes, the boundaries are not statistically robust. Samples that lacked Nb or Y data were classified using their Zr/TiO<sub>2</sub> ratio. Samples that lacked zirconium or TiO<sub>2</sub> data were removed from the database.

After samples were classified into rock types using immobile element ratios, their magmatic affinities were investigated using the schemes of Barrett and MacLean (1999) and Ross and Bédard (2009) as shown in Table 3. Tholeiitic volcanic rocks can be distinguished from calc-alkaline 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 (Jenner, 1996; Kerrich and Wyman, 1996; Rollinson, 1993). Although the original Barrett and MacLean (1999) scheme was recently refined by Ross and Bédard (2009), the original values were retained here because the Ross and Bédard (2009) scheme was

**Table 3. Discrimination criteria for identifying tholeiitic, transitional and calc-alkaline volcanic rocks using immobile element ratios from Barrett and MacLean (1999) and Ross and Bédard (2009)**

	Zr/Y	Th/Yb	La/Yb
<i>Barrett and MacLean (1999)</i>			
Tholeiitic	<4.5	<0.25	<3.0
Transitional	4.5 – 7.0	0.25 – 0.65	3.0 – 6.0
Calc-alkaline	>7.0	>0.65	>6.0
<i>Ross and Bédard (2009)</i>			
Tholeiitic	<2.8	<0.35	<2.6
Transitional	2.8 – 4.5	0.35 – 0.8	2.6 – 5.3
Calc-alkaline	>4.5	>0.8	>5.3

constructed using only a small proportion of felsic rocks (<4% were rhyolitic), and consequently permits insufficiently detailed discrimination for the felsic petrochemical suites FI to FIV.

According to the Ross and Bédard (2009) Zr/Y scheme, the FI, FII and FIIIa suites are of calc-alkaline affinity, with only the FIIIb suite classified as transitional to tholeiitic. The Barrett and MacLean (1999) scheme was constructed primarily for discrimination of mafic and felsic volcanic sequences in VMS systems and has been applied to numerous deposits worldwide. According to Zr/Y ratios in this instance, FI and FII suite are calc-alkaline, FIIIa is transitional and FIIIb (and FIV) tholeiitic. For samples in this study, Th/Yb allowed little distinction between the majority of samples, so the Zr/Y and Th/Yb ratios were used for classification purposes. The use of the term ‘transitional’ here refers to rocks intermediate between tholeiitic and calc-alkaline compositions. It does not refer to rocks intermediate between subalkaline and alkaline compositions.

Following this classification, chondrite-normalized La/Sm, Dy/Yb and La/Yb ratios were calculated using values from McDonough and Sun (1995). Some consideration was given as to whether samples displayed significant europium variations, as large positive anomalies can indicate local hydrothermal alteration. Niobium anomalies were also calculated, relative to chondrite-normalized thorium and lanthanum values. For samples that lacked grid coordinates (i.e. those from Whitford and Ashley, 1992; Yeats and Groves, 1998; Sharpe and Gemmell, 2001), prospect coordinates from the Western Australian Department of Mines Petroleum MINEDEX database (GSWA, 2015b) were used. Coloured contour maps for felsic rocks and granitic rocks from the Yilgarn Craton were produced in ArcGIS using simple prediction Kriging. Granite data were compiled from the Western Australia Department of Mines Petroleum GeoChem Extract database (GSWA, 2014b), the Geoscience Australia OZCHEM database (Geoscience Australia, 2007), and several unpublished studies.

## Results: prospectivity of intermediate and felsic rocks

The geochemistry of felsic and intermediate volcanic and volcanoclastic rocks of the Yilgarn Craton is presented in Figures 26 to 35. Through comparisons to the VMS-rich Abitibi greenstone belt of Canada (Leshner et al., 1986; Barrie et al., 1993) and Pilbara Craton of Western Australia, it is clear these rocks display a similar, broad range of geochemical characteristics (Fig. 27), ranging from unprospective (FI affinity) to highly prospective (FIIIb affinity). VMS-associated (and prospective) felsic rocks are characterized by (after Hollis et al., 2015):

- high  $\text{SiO}_2$  in weakly altered rocks
- tholeiitic to transitional Zr/Y and La/Yb values and FII to dominantly FIII characteristics (Fig. 28)
- flattish REE profiles ( $\text{La}/\text{Sm}_{\text{CN}} < 3$ ;  $\text{Dy}/\text{Yb}_{\text{CN}}$  ratios  $\sim 1$ ) (Figs 29, 30)
- high HFSE (Y, Nb, Zr, Sc) concentrations (Fig. 31)
- high  $\text{Sc}/\text{TiO}_2$  and  $\text{Sc}/\text{V}$
- low V and Th/Yb ( $\text{Th}/\text{Yb} < 2$  and  $\text{Th} > 5$  ppm)

The high HFSE and HREE concentrations allow prospective units to be distinguished from barren felsic rocks using ratios (e.g. Zr/Y,  $\text{Sc}/\text{TiO}_2$ ) and absolute concentrations (e.g. A-type affinities). Felsic rocks associated with VMS mineralization are restricted to four time intervals in the Youanmi Terrane, as described by Hollis et al. (2015): 1)  $> 2.9$  Ga greenstone belts (e.g. Golden Grove, Weld Range, Ravensthorpe, Twin Peaks, Talling); 2) c. 2815 Ma Yaloginda Formation and Kantie Murdana Volcanics Member (e.g. Quinns/Austin, Narndee, Windimurra, Youanmi, Copper Hills); 3) c. 2750 Ma Greensleeves Formation (e.g. Hollandaire, Chesterfield, Dalgaranga, Jillewarra, Emily Well, Abbotts area); and 4) c. 2725 Ma Gum Creek greenstone belt. In the Eastern Goldfields Superterrane, VMS-associated and prospective felsic rocks are mainly 2690–2680 Ma in age (e.g. Teutonic Bore, Jaguar, Melita, Spring Well, King) with the exception of Anaconda and Nimbus (Hollis et al., 2015, in press).

It is important to note that felsic rocks which display unprospective geochemical signatures (i.e. steep, FI, TTG-like REE profiles) have also been recognized from each of the episodes described above (see Hollis et al., 2015). Although these felsic rocks are considered unprospective hosts for mineralization, they may be present in association with FIII type rocks in the local stratigraphy of a number of deposits (e.g. Golden Grove Scuddles hangingwall dacite, Jaguar hangingwall andesite; see discussion in Hollis et al., 2015). Thus, it is the recognition of FIII type characteristics that is important, not the absence of FI type signatures.

In Figure 28, felsic volcanic rocks from each area of the Yilgarn Craton are plotted on the classic VMS fertility plot of Leshner et al. (1986). It is evident that, in addition

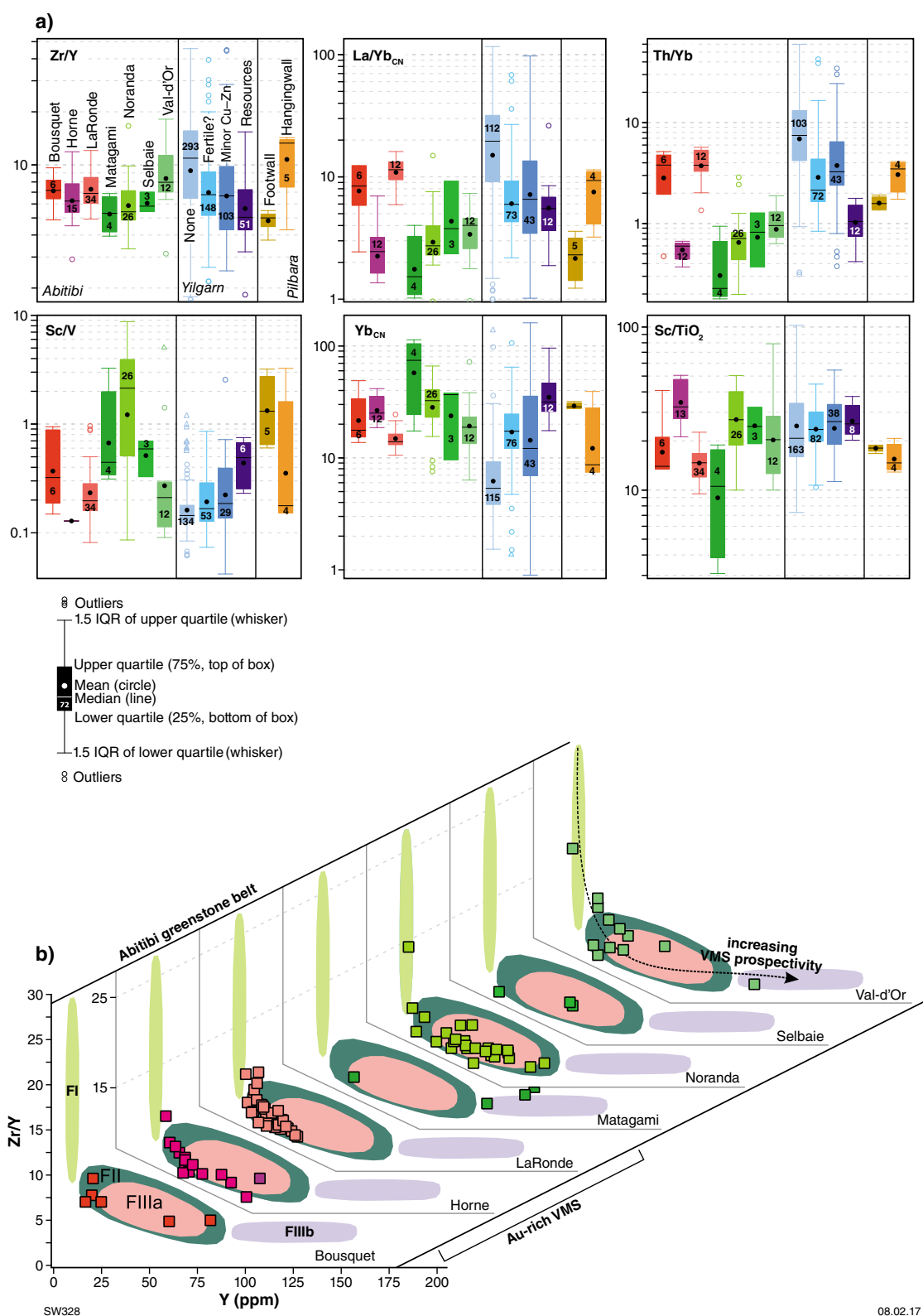
to areas where significant VMS resources have already been identified (e.g. Golden Grove, Jaguar/Teutonic Bore, Hollandaire, Quinns, Ravensthorpe), many other areas contain felsic rocks that are geochemically similar. These include areas where minor base metal occurrences have been identified and new target areas for exploration. Areas considered prospective based on the Leshner et al. (1986) diagram include areas in which subeconomic VMS-style mineralization has been recognized. Localities (Fig. 24) include Abbotts, Anaconda, Bore Well, Chesterfield, Copper Hills, Dalgaranga, Emily Well, Gullewa, Gum Creek, Jillewarra, Narndee, Weld Range, Windimurra north, Yalgoo–Singleton north, Youanmi. However, it also highlights areas in which VMS-style mineralization has not been identified: Big Bell, Koolanooka south, Lake Weelhamby, Marda, Melita, Mount Venn(?), Meekatharra, west of Quinns, Spring Well, south of Jungle Pool, Welcome Well and the Mount Gill area of the Yamarna Terrane (Tobin Hill Formation; Fig. 5).

High concentrations of the HFSE (and low Th/Yb and La/Yb ratios) further discriminate which areas can be considered VMS prospective (Figs 31, 32). Ratios are plotted spatially for the entire craton (Fig. 33a–g) and using an Additive Index of ratios considered favourable for VMS prospectivity (Fig. 33h). For the Additive Index, samples were assigned one point for each of the following criteria:

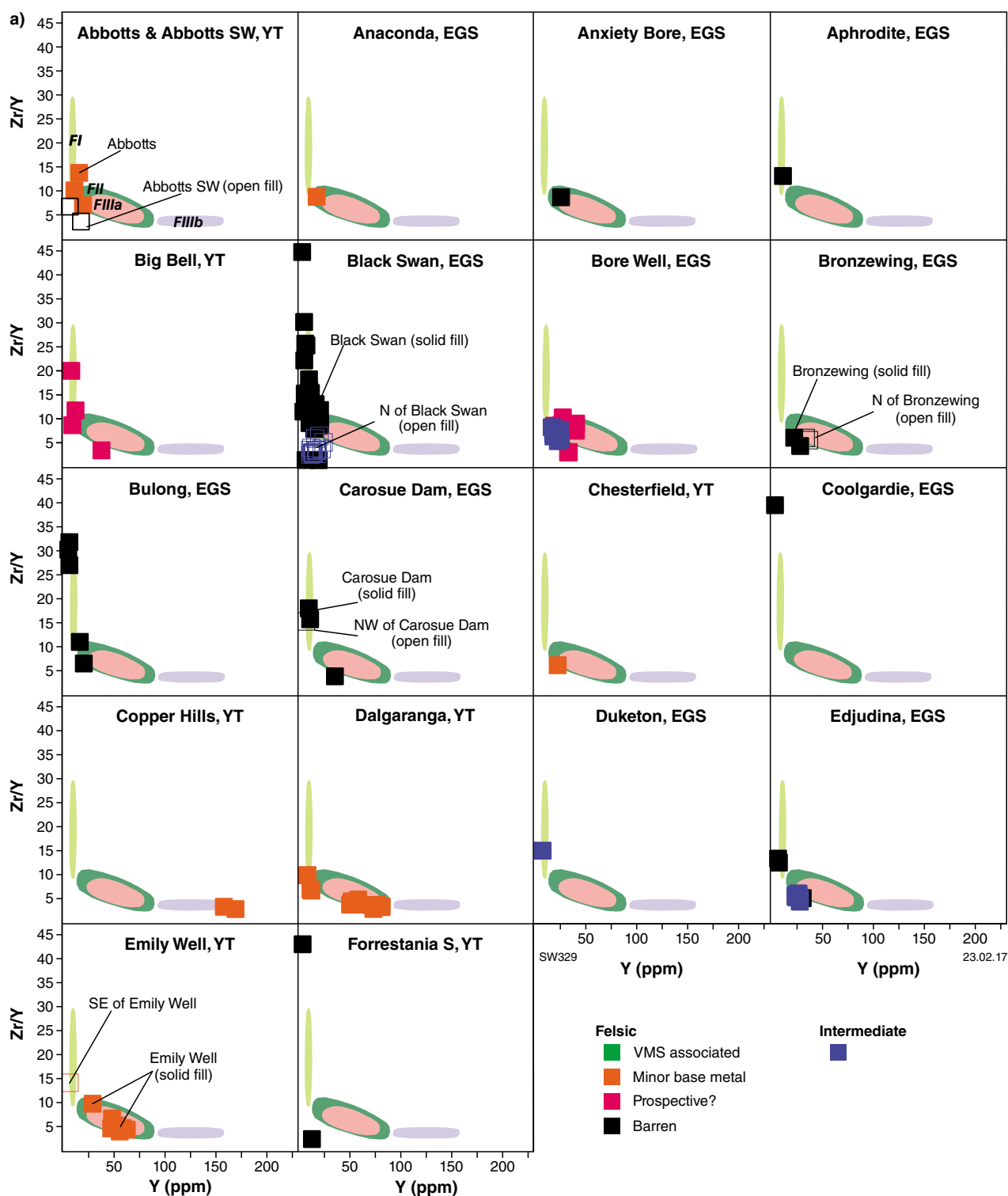
Zr/Y  $< 5$ ,  $\text{La}/\text{Yb}_{\text{CN}} < 5$ ,  $\text{Th}/\text{Yb} < 2$ ,  $\text{Yb}_{\text{CN}} > 45$ , Y  $> 50$  ppm,  $\text{Sc}/\text{V} > 0.7$ , Zr  $> 275$  ppm, Nb+Y+Hf+Ta  $> 85$  ppm,  $\text{Sc}/\text{TiO}_2 > 30$ .

All significant known areas of VMS mineralization have been correctly identified where data are available. Importantly, this method also highlights the prospectivity of the Bore Well and Mount Gill areas (see Discussion). Other areas such as Bulong, Edjudina, Gindalbie, Green Dam, Jundee, Lake Johnston, Laverton and Leonora may be of interest due to low Th/Yb and La/Yb ratios.

All intermediate and felsic volcanic rock data are contoured with granitic rocks from the Yilgarn Craton in Figures 34 and 35. It is evident that low Zr/Y, Th/Yb and La/Yb ratios denote areas of prospective crust, whereas areas of the craton dominated by FI type felsic rocks and late granites can be considered unprospective. Areas defined by low Zr/Y include Koolanooka, Golden Grove, the area surrounding the 2815–2800 Ma intrusive rocks (e.g. Narndee, Windimurra), the southeastern part of the Gum Creek greenstone belt, the Dalgaranga greenstone belt, and an area of crust in the vicinity of Abbotts, Hollandaire, Glenview and Copper Hills (Fig. 34). The latter is broadly equivalent to the northern region of the Cue Zone (Fig. 2a), which was considered by Huston et al. (2014) to be particularly VMS prospective. In the Eastern Goldfields Superterrane, contoured La/Yb ratios (Fig. 35) are broadly equivalent to the Kurnalpi rift zone identified by Huston et al. (2014) using Pb and Nd isotopic data. Major VMS occurrences are located along the margins of this zone defined by La/Yb ratios (Nimbus, King, Jungle Pool, Anaconda, Duketon and Teutonic Bore) along with many other areas considered prospective (e.g. Bore Well, Welcome Well, Gindalbie, Melita, Spring Well, Edjudina).



**Figure 27.** a) Tukey (box and whisker) plots for intermediate and felsic rocks from the Yilgarn Craton, Pilbara Craton and VMS-bearing camps of the Abitibi greenstone belt, Canada, containing >20 Mt of ore (after Hollis et al., 2015). Felsic rocks from the Yilgarn Craton are sorted into the following groups: 1) areas with no base metal mineralization (e.g. Kambalda, Kalgoorlie); 2) areas with minor Cu–Zn mineralization (e.g. Dalgara, Windimurra, Namdee, Chesterfield, Jungle Pool); 3) areas with significant VMS resources (e.g. Teutonic Bore, Jaguar, Quinns, Golden Grove, Hollandaire); 4) areas where no base metal mineralization has been identified that may VMS prospective based on their geochemistry (e.g. Melita, Bore Well). IQR, Interquartile range; b) prospectivity of felsic rocks from the Abitibi greenstone belt according to Leshar et al. (1986). All stacked plots are at the same scale with Zr/Y values indicated on the y-axis. Modified from Hollis et al. (2015)



**Figure 28.** Prospectivity of intermediate and felsic rocks from the Yilgarn Craton according to the Lesher et al. (1986) characterization of Archean felsic volcanic rocks in the Superior Province. a)–e) areas arranged alphabetically. Pale green, FI; dark green, FII; pink, FIIIa; grey, FIIIb. Localities are shown in Figure 24: EGS, Eastern Goldfields Superterrane; YT, Youanmi Terrane; SWT, South West Terrane

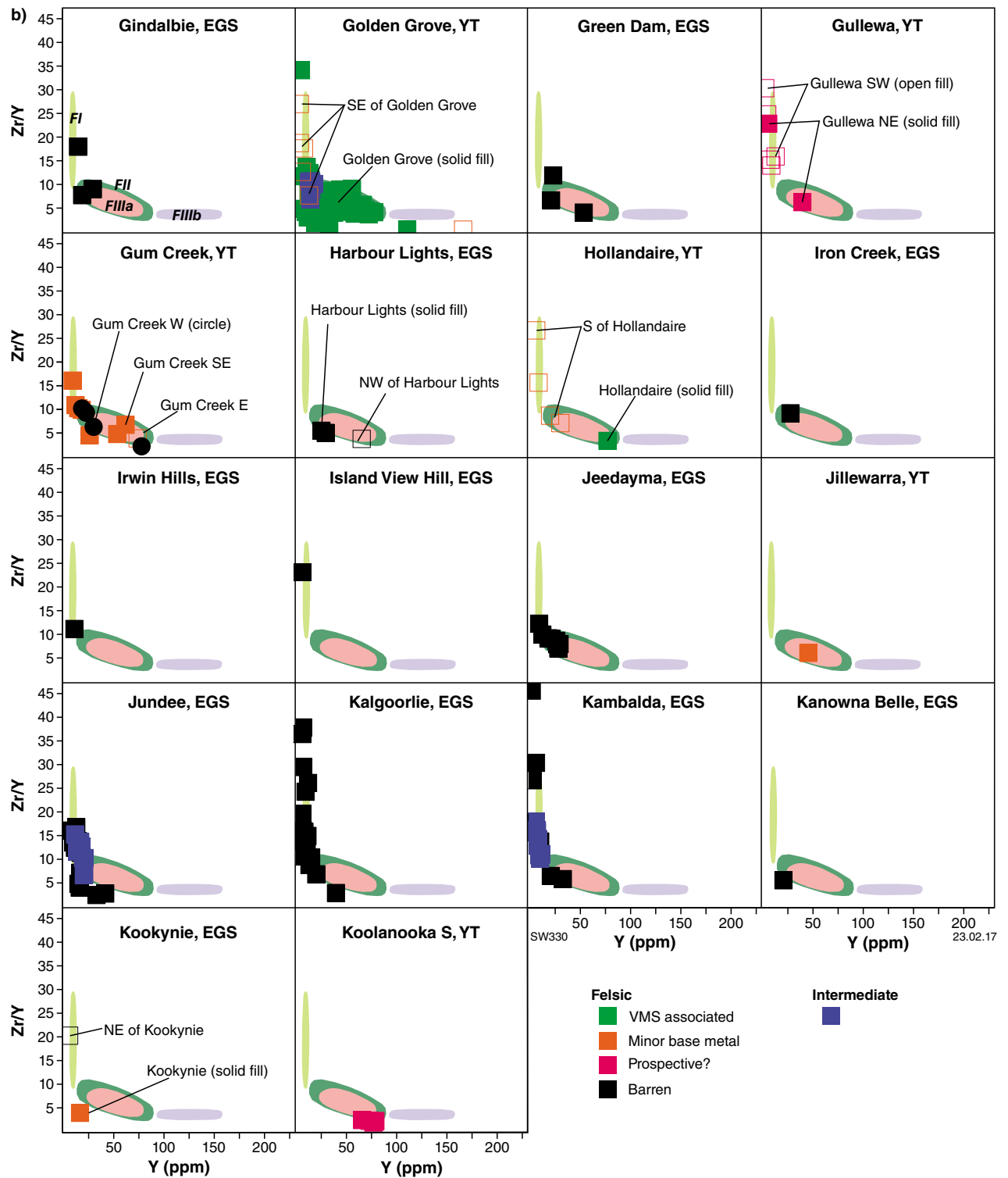


Figure 28. continued

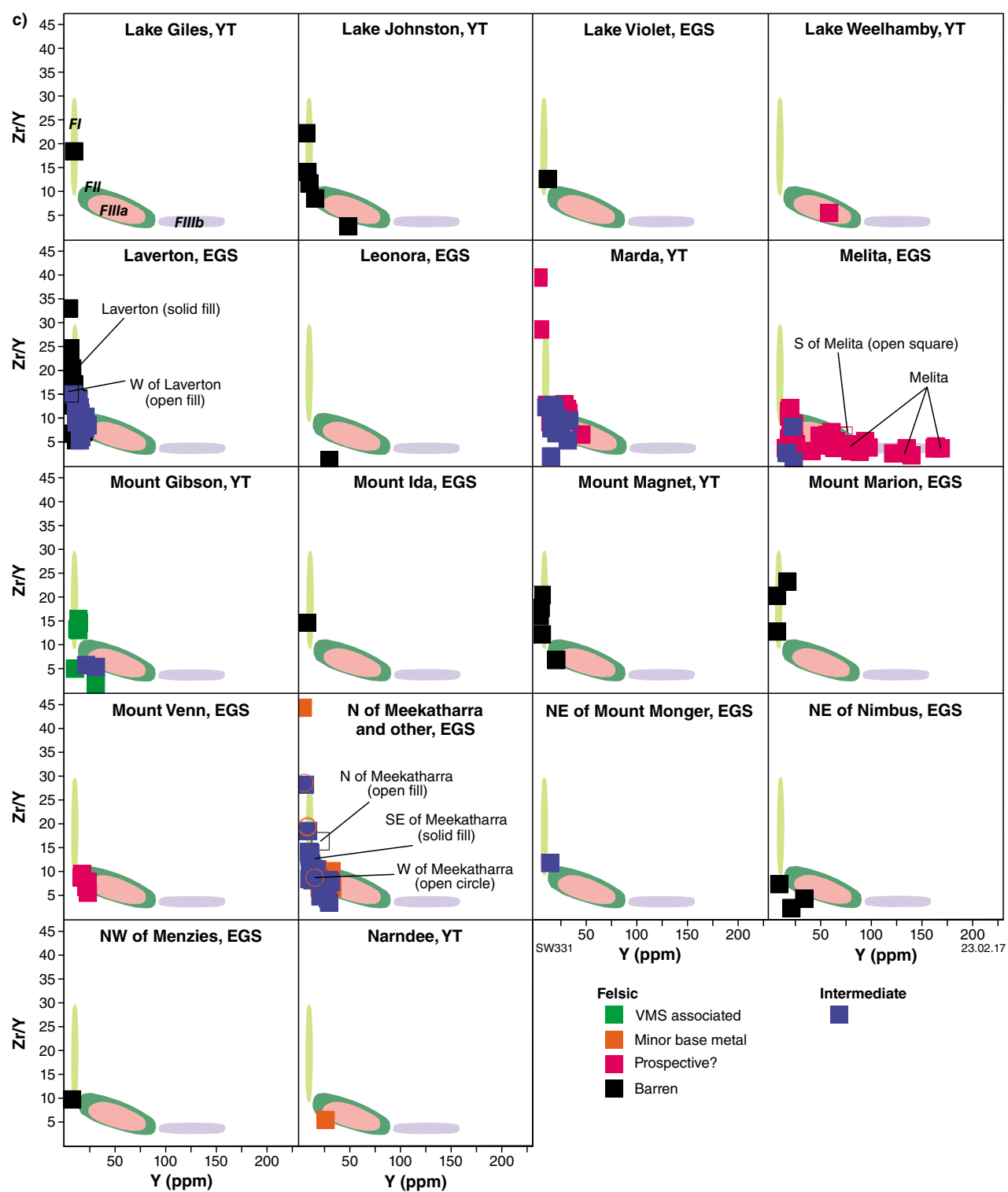
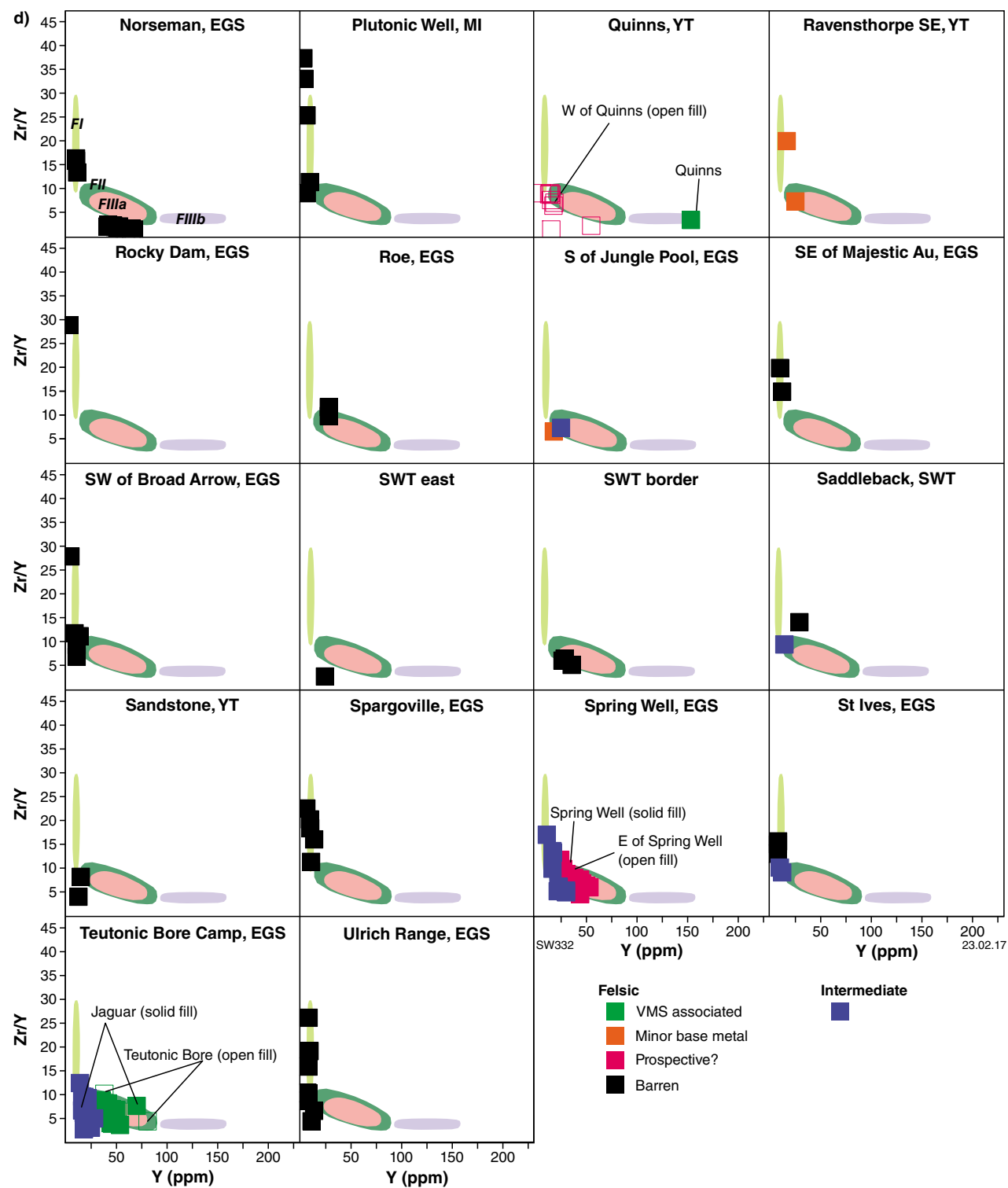


Figure 28. continued





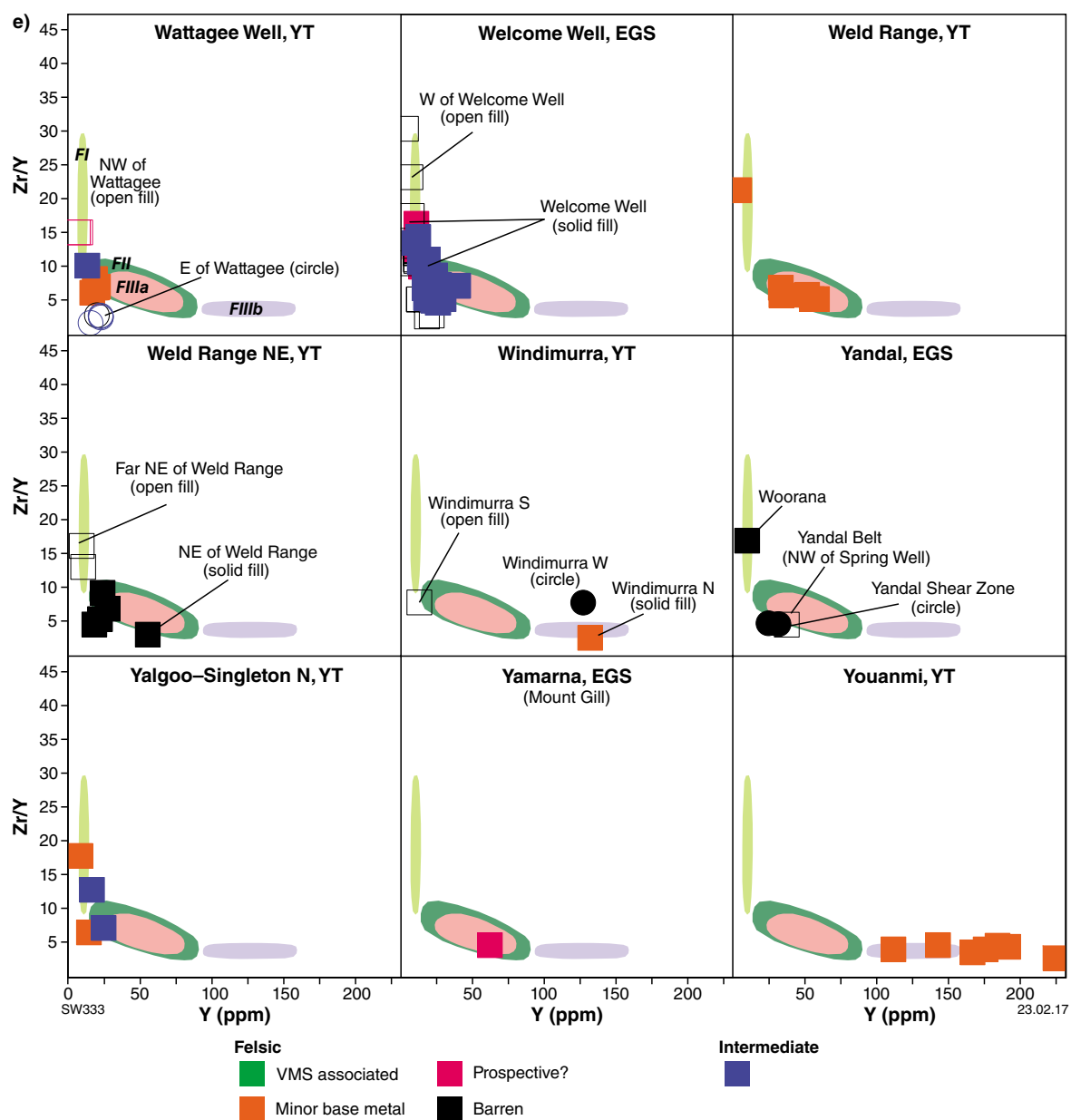
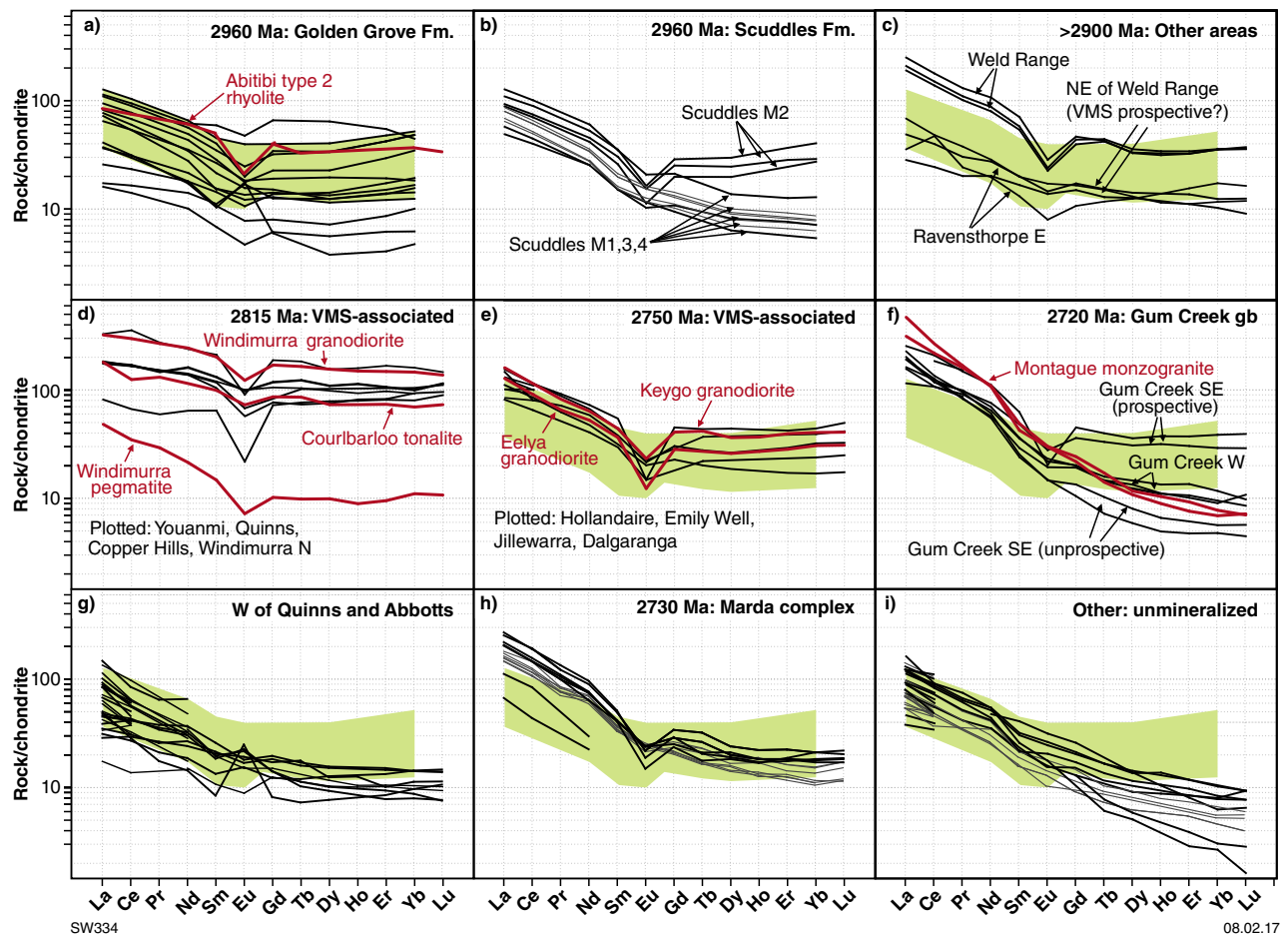


Figure 28. continued



**Figure 29.** Selected chondrite-normalized REE profiles for intermediate and felsic rocks of the Youanmi Terrane. Green shading reflects least altered and mineralized felsic rocks from the Golden Grove Formation. Intermediate and felsic rocks are indicated by faint and heavy lines, respectively. The geochemistry of several synvolcanic intrusive rocks are also shown (data from Ivanic et al., 2012; GSWA, 2016a; Champion and Cassidy, 2002b). Modified from Hollis et al. (2015)

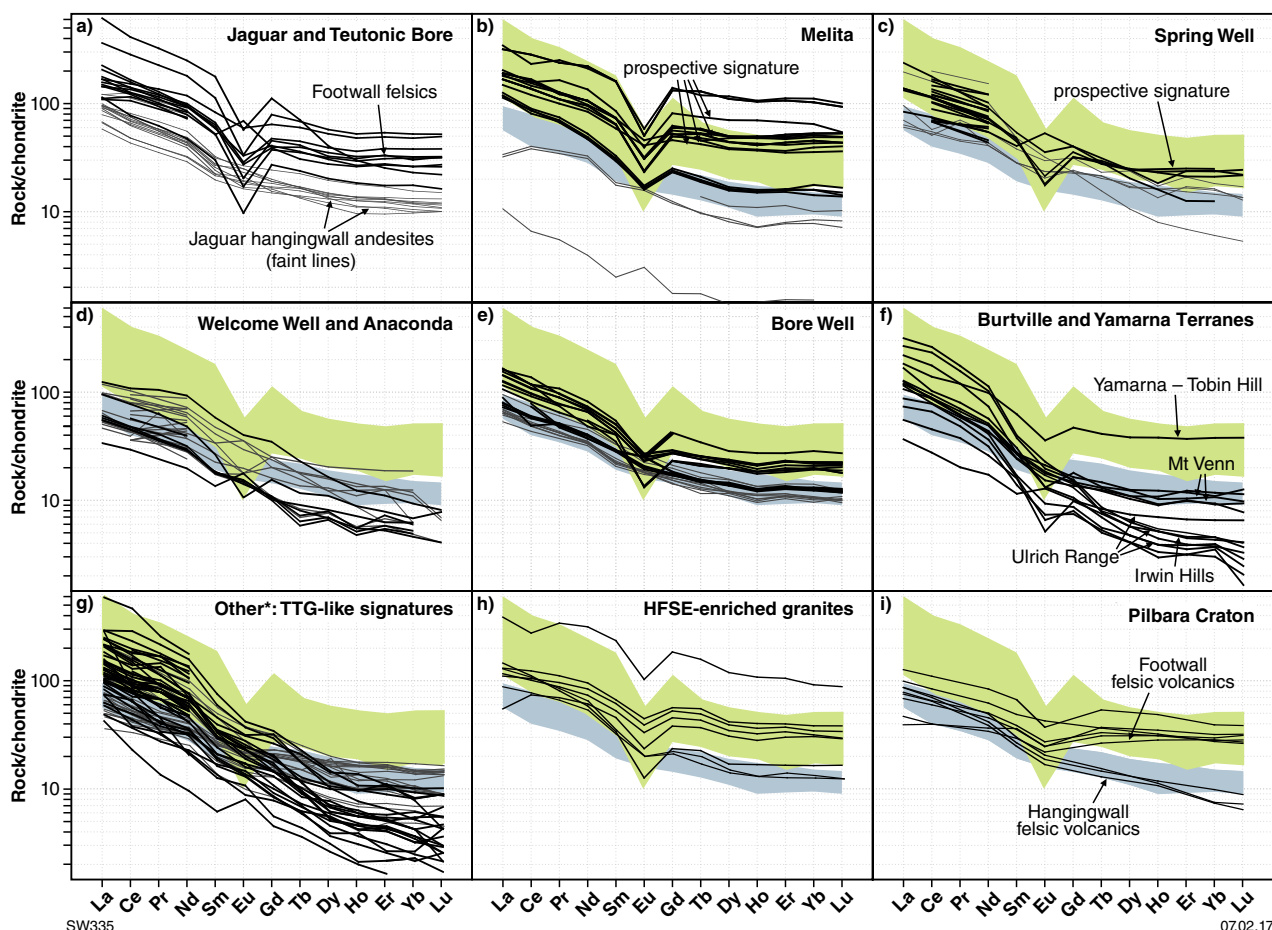
## Discussion

### Timing of VMS mineralization

Detailed geological mapping, combined with regional geophysical surveys, extensive geochemistry, and high-resolution U–Pb zircon geochronology, have resulted in a vastly improved understanding of the geology of the Yilgarn Craton and its potential to host VMS mineralization. Van Kranendonk et al. (2013) presented a revised stratigraphy for the long-lived, and proposed autochthonous development of the Murchison Domain of the Youanmi Terrane. Using this stratigraphy, and an extensive database of published U–Pb zircon ages from the Yilgarn Craton, four main periods of VMS mineralization have been recognized in the northern Youanmi Terrane (Figs 1b, 3; Hollis et al., 2015) at >3000–2930 Ma, c. 2815 Ma, 2760–2745 Ma and c. 2722 Ma:

- The 2960–2930 Ma succession at Golden Grove hosts significant copper–zinc resources at Gossan

Hill (15.9 Mt at 1.5% Zn and 2.6% Cu), Scuddles (10.5 Mt at 11.7% Zn and 1.2% Cu), at depth between the two deposits (e.g. Amity, Ethel), and at Gossan Valley/Felix. The 3000–2950 Ma Ravensthorpe greenstone belt has historically accounted for much of Western Australia's copper production. Synvolcanic copper–gold and copper–zinc mineralization is primarily hosted in the c. 2989 Ma Annabelle Volcanics within two kilometres from the contact of the synvolcanic Manyutup Tonalite (M Barley, personal communication in Witt, 1999). Other VMS-style base metal mineralization which formed prior to 2900 Ma has been recognized at Weld Range (e.g. c. 2969 Ma; Wingate et al., 2008; Guillianse, 2014), in the Tallering greenstone belt (c. 2935 Ma; Pidgeon and Wilde, 1990b), the Twin Peaks greenstone belt (c. 3014? Ma; Pidgeon et al., 1990b) and at Mount Gibson (c. 2930 Ma; Yeats et al., 1998). Base metal occurrences near Bunnawarra (northwest of Golden Grove) may be similar in age to those described above (>2.9 Ga). New U–Pb geochronology and GSWA mapping currently under way around Golden

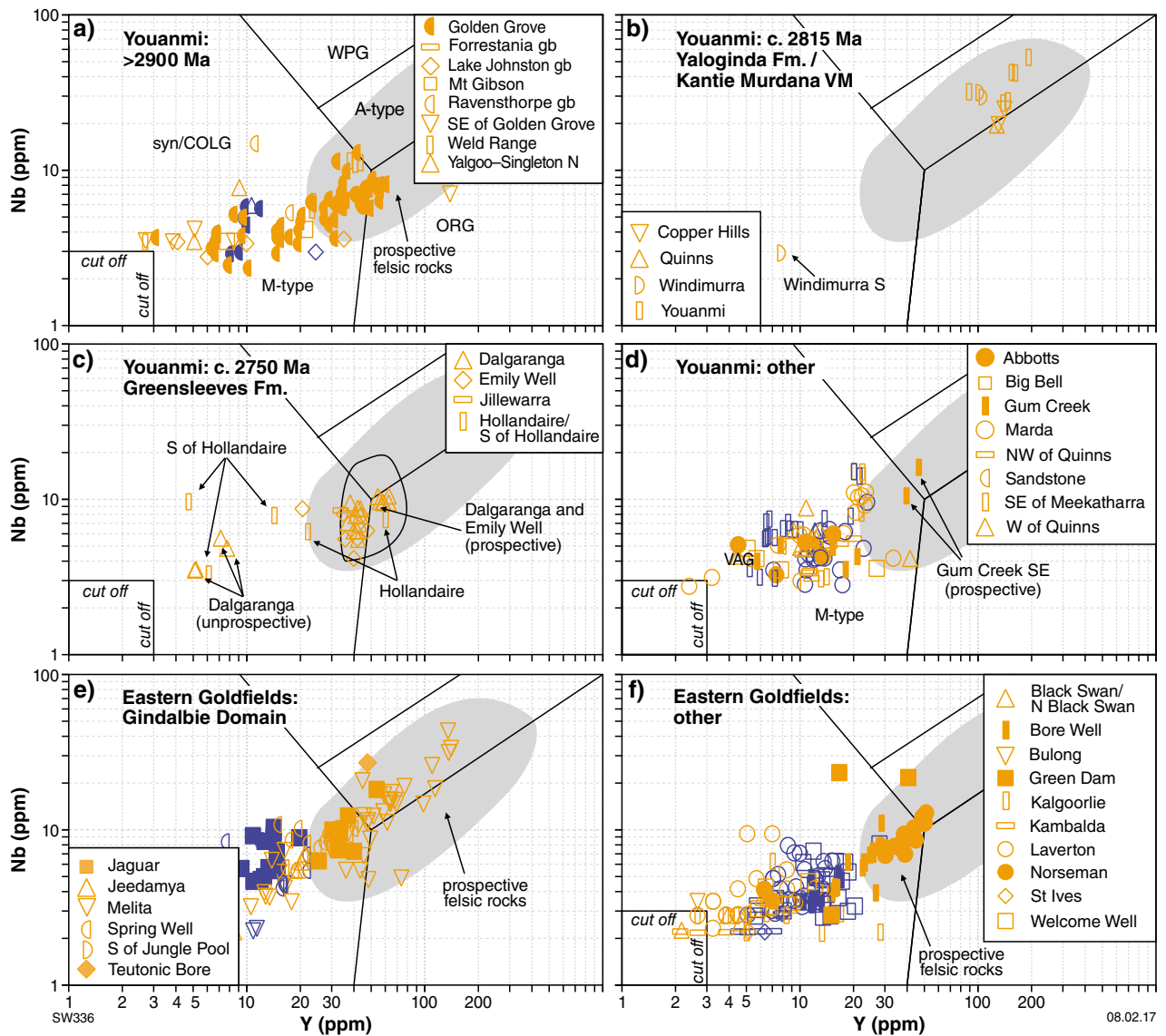


**Figure 30.** Selected chondrite-normalized REE profiles for: a) to g) felsic and intermediate volcanic rocks of the Eastern Goldfields Superterrane; h) HFSE-enriched granitic intrusions near Teutonic Bore (data from Champion and Cassidy, 2002a); and i) VMS-associated felsic rocks from the Pilbara Craton. Intermediate and felsic rocks are indicated by faint and heavy lines respectively. Green shading reflects petrochemically prospective felsic rocks from Jaguar (Belford et al., 2015) and Teutonic Bore (CSIRO, unpublished data) as represented in Figure 30a. Grey shading reflects the Jaguar hangingwall andesites field. Localities with TTG-like REE profiles shown in Figure 30g include: Aphrodite, Bronzewing, King (Erayinia), Coolgardie, E of Norseman, Ida Hill, Jundee, Kalgoorlie, Kanowna Belle, Lake Giles, Lake Violet, Lotus, Mt Ida, Mount Monger, Murphy Hills, northwest of Menzies, Spargoville, St Ives, Yandal, Wallaby. Localities shown in Figure 24. Modified from Hollis et al. (2015)

Grove and Mount Gibson aims to refine the >2.9 Ga stratigraphy of the Yalgoo–Singleton greenstone belt and Murchison Domain as a whole.

- A second, short-lived, major episode of VMS mineralization at c. 2815 Ma in the 2825–2805 Ma Norie Group at Austin (c. 2817 Ma; Wingate et al., 2011a), Just Desserts (>2813 Ma; Cassidy et al., 2002) and Chunderloo is associated with petrochemically prospective felsic rocks of the Yaloginda Formation. Geochemically similar felsic rocks of the Kantie Murdana Volcanics Member of the Norie Group also host significant VMS mineralization overlying the large 2815–2800 Ma igneous complexes of the central Youanmi Terrane (Boodanoo and Meeline suites). Base metal occurrences associated with these

igneous complexes have been identified at Narndee (e.g. Narndee, Yalanga Bore, Quandong Well), Youanmi (e.g. Manindi, Pincher Well, Shirley Bore, Ram Well, Youangarra), Windimurra (e.g. Rowes, Saffron, Rosemary, Ann, Paynesville North) and Lady Alma (e.g. Copper Hills, Gabanintha) igneous complexes. SHRIMP U–Pb zircon geochronology from Narndee area (c. 2818 Ma; Wingate et al., 2012c) and Manindi (c. 2814 Ma; Nelson, 2002) is within uncertainty of the timing of VMS mineralization in the felsic volcanic units of the Yaloginda Formation. There are no published U–Pb zircon ages for felsic volcanic rocks which host VMS mineralization near Windimurra, Chunderloo and Copper Hills, the last of which is associated with the mafic–ultramafic Lady Alma Igneous Complex of the Meeline Suite.



**Figure 31. Petrochemical affinity of selected intermediate and felsic rocks from the Yilgarn Craton according to Nb and Y concentrations. Grey shading represents the VMS-prospective field (I- to A-type affinities) based on high HFSE concentrations; gb, greenstone belt**

- In the 2800–2735 Ma Polelle Group (Fig. 25), VMS 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), Mount Mulcahy, Emily Well, Jillewarra/Chesterfield, Conroy, Mungarra Gully, Wattagee and in the Dalgara greenstone belt (e.g. Lasoda, Superior). Areas of the Greensleeves Formation that contain petrochemically prospective felsic rocks host copper–zinc occurrences, whereas petrochemically unprospective areas are barren (Fig. 28). SHRIMP U–Pb zircon geochronology from Eelya Hill has yielded a date of  $2746 \pm 4$  Ma (Wingate et al., 2012a), within uncertainty of dates obtained from the Dalgara greenstone belt (c. 2745 Ma; Pidgeon and Hallberg, 2000). Slightly older ages for the volcanic succession near Emily Well (c. 2761 Ma; Pidgeon and Hallberg, 2000) and the Hollandaire mine stratigraphy ( $2759.5 \pm 0.9$  Ma; Hayman et al., 2015) suggest base metal mineralization here may be at a deeper stratigraphic level, towards the base of the Greensleeves Formation. Other areas that appear prospective for VMS mineralization include Abbots, Big Bell and south of Hollandaire (Tuckabianna SE).
- VMS mineralization in the Gum Creek greenstone belt of the Southern Cross Domain (e.g. The Cup, Bevan) is probably associated with 2735–2700 Ma felsic volcanic and carbonaceous sedimentary rocks, which are coeval with the Glen Group in the Murchison Domain. Felsic volcanic rocks near the Bevan base metal occurrence have a SHRIMP U–Pb zircon age of  $2722 \pm 6$  Ma (Bodorkos et al., 2006).



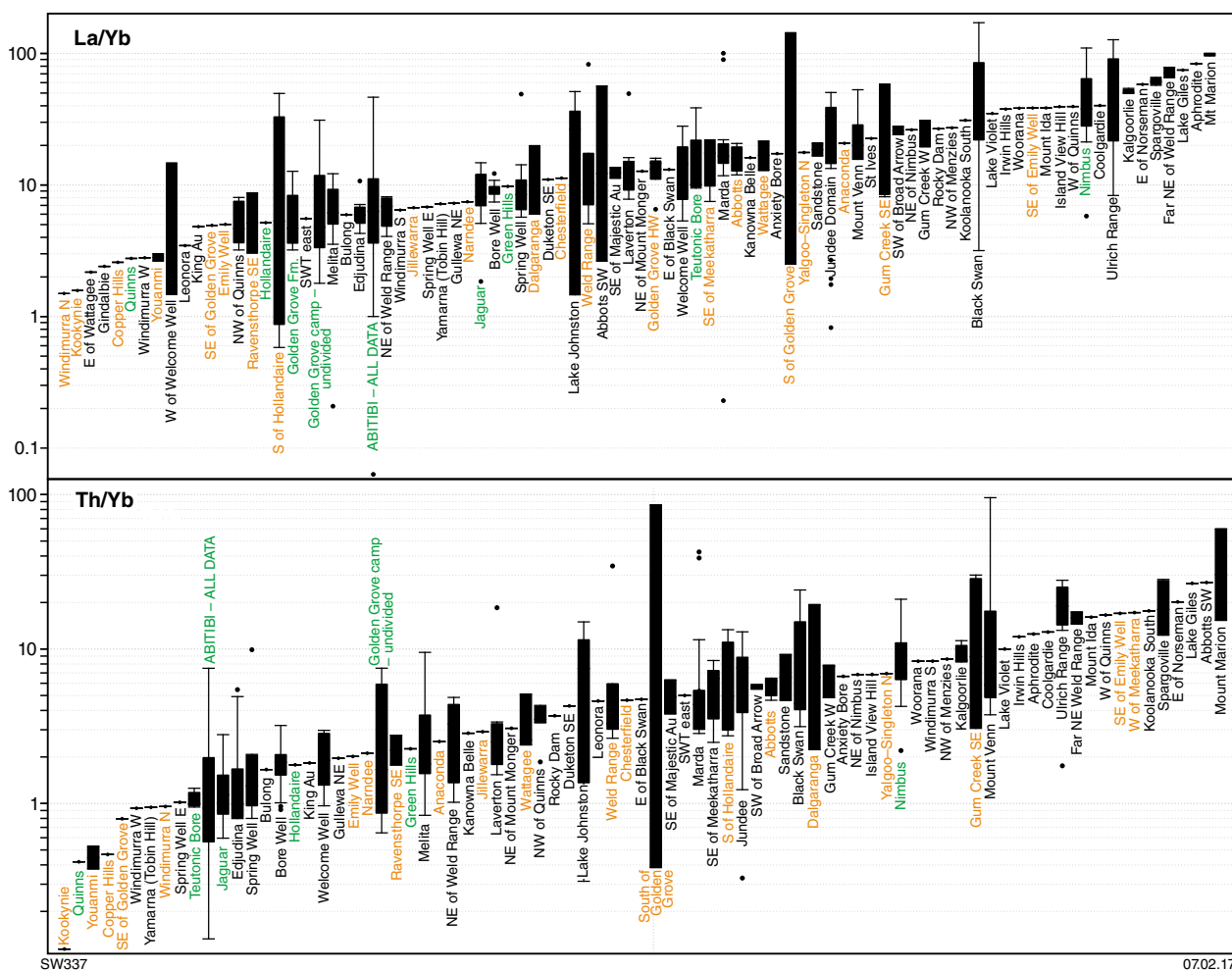


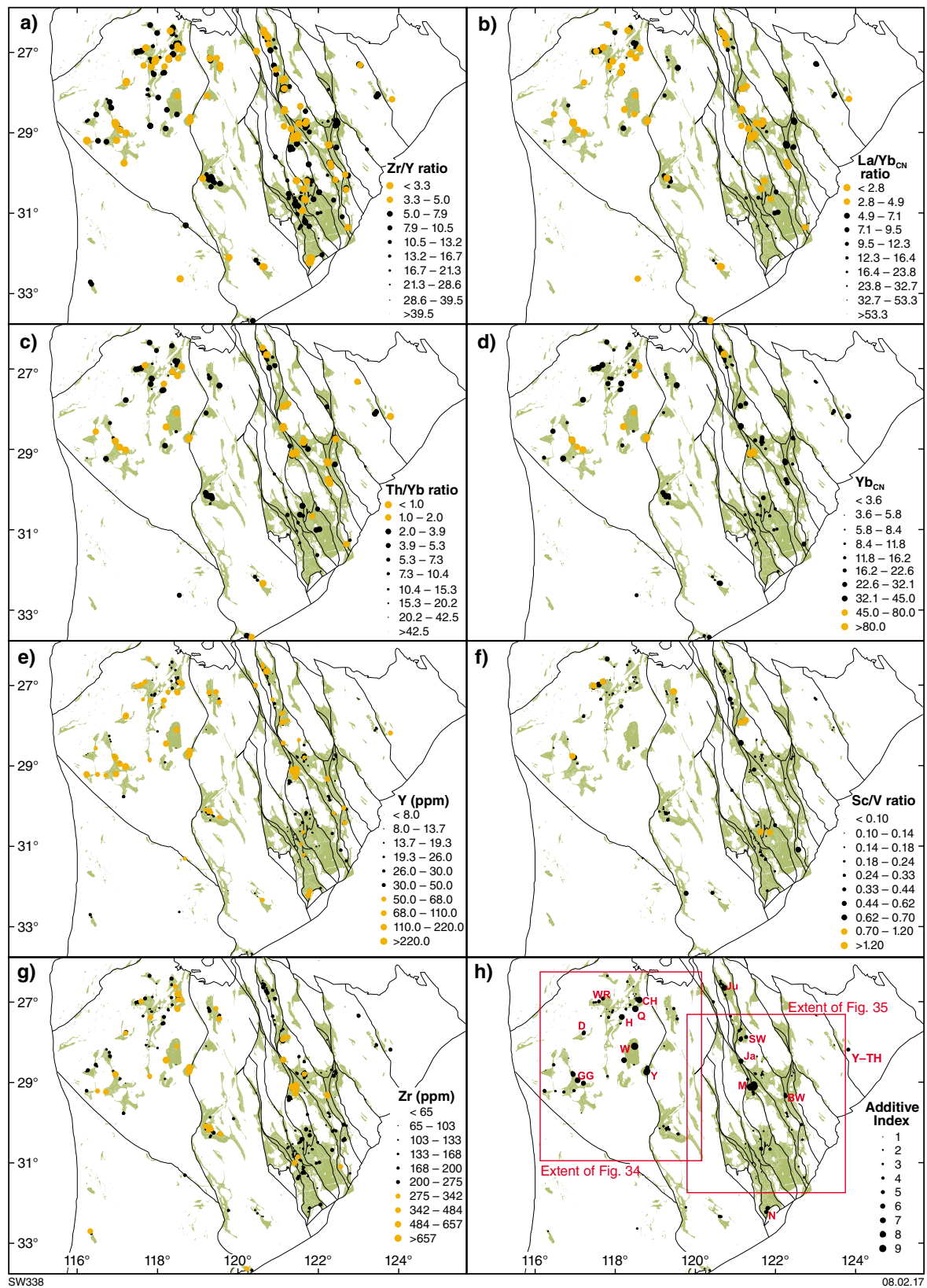
Figure 32. Tukey (box and whisker) plots of La/Yb and Th/Yb ratios for intermediate and felsic rocks from the Yilgarn Craton (sorted according to lowest average ratios). Localities highlighted refer to areas with significant VMS resources (green) or minor base metal mineralization (orange)

Although there are a number of base metal occurrences in the Eastern Goldfields Superterrane (e.g. Teutonic Bore camp, Jungle Pool, Nimbus, Anaconda, Erayinia, Rungine), the timing of mineralization at several of the localities is not well constrained. In the northern Gindalbie Domain (Cassidy et al., 2006), significant VMS mineralization at c. 2690 Ma in the Teutonic Bore camp (c. 2692 Ma; Nelson 1995a) is associated with largely bimodal volcanic complexes and deep-marine, argillaceous sedimentary rocks. SHRIMP U–Pb zircon geochronology from felsic volcanic rocks of the Melita Formation (Wyche et al., 2016) has produced similar, albeit slightly younger, dates of c. 2683 Ma (Brown et al., 2002) and may constrain the timing of nearby VMS mineralization at Jungle Pool to the southeast. The close association between felsic volcanic rocks and spinifex-textured komatiitic flows at Anaconda, together with a date of  $2698 \pm 5$  Ma (Nelson, 2005), suggests VMS mineralization at Anaconda is hosted within an older sequence than that of the Gindalbie Domain (e.g. Czarnota et al., 2010) and may be similar to

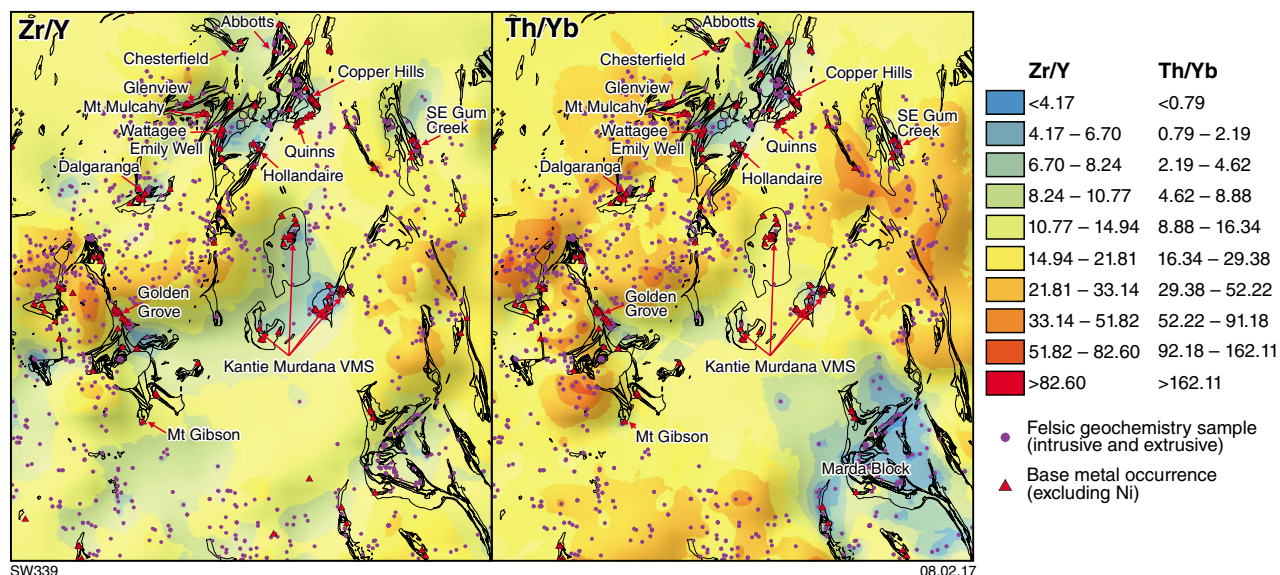
2715–2705 Ma felsic sequences in the Boorara Domain. Nimbus has recently produced two SHRIMP U–Pb ages of c. 2705 Ma constraining the local stratigraphy to the Kambalda Sequence (Fig. 4). The specific ages of VMS mineralization at Erayinia, Brilliant Well, Rungine and Balagundi are unknown. Nevertheless, all existing data suggest that VMS mineralization in the Eastern Goldfields Superterrane, and particularly the western part, is younger than the last phase of VMS mineralization in the Youanmi Terrane.

The South West Terrane of the Yilgarn Craton comprises strongly deformed, high-grade granite–gneiss, metasedimentary and meta-igneous rocks intruded by 2750–2620 granitic rocks and pegmatites (Mole et al., 2012). Supracrustal successions may range in age back to c. 3010 Ma in the Chittering, Jimperding and Balingup metamorphic belts and the Wongan Hills greenstone belt, and have ages in the range 2715–2675 Ma in the Saddleback and Moranup greenstone belts (Fig. 1b).

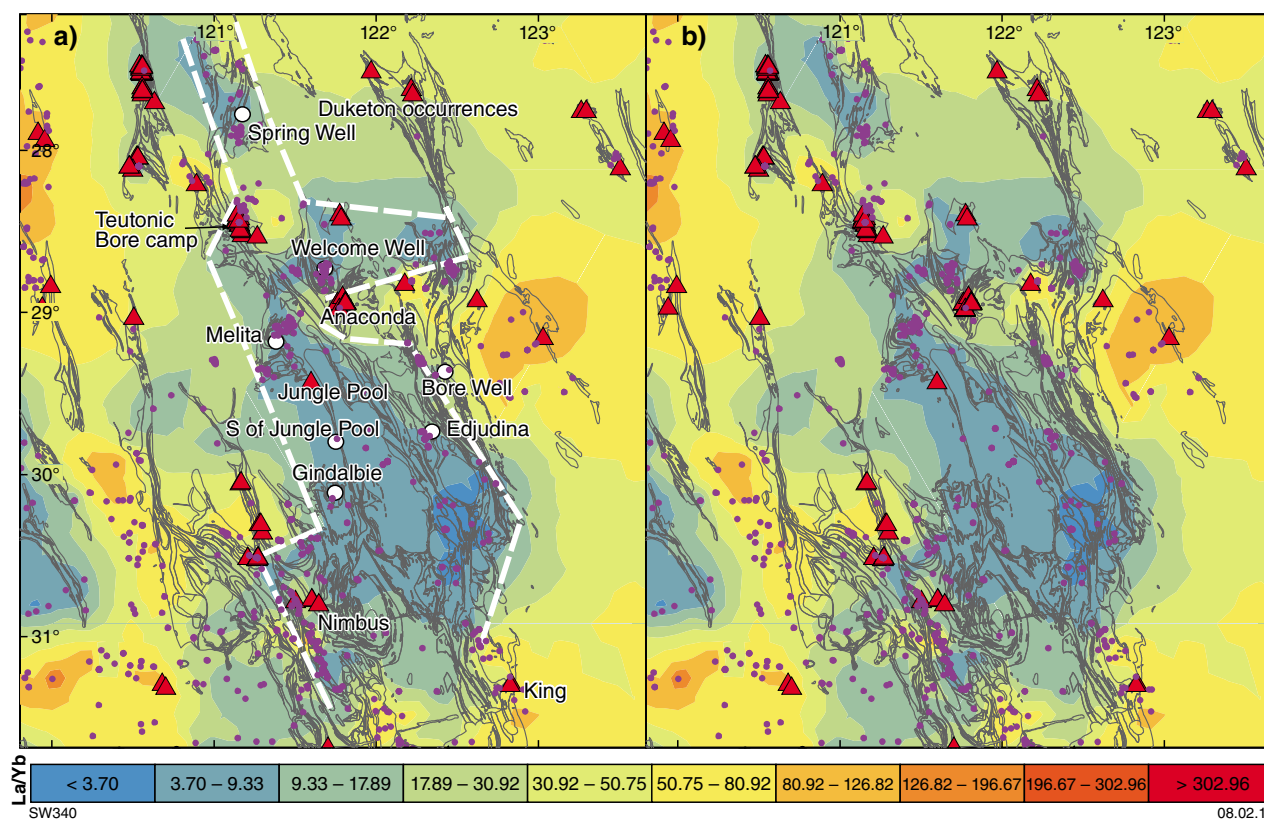




**Figure 33. Prospectivity of intermediate and felsic rocks from the Yilgarn Craton according to different immobile element concentrations and ratios. Yellow symbols represent samples included in the Additive Index: a) Zr/Y ratio; b) La/Yb<sub>CN</sub> ratio; c) Th/Yb ratio; d) Yb<sub>CN</sub> concentration; e) Y concentration; f) Sc/V ratio; g) Zr concentration; h) Additive Index. In the Additive Index, samples were assigned one point for each of the following criteria: Zr/Y < 5, La/Yb<sub>CN</sub> < 5, Th/Yb < 2, Yb<sub>CN</sub> > 45, Y > 50 ppm, Sc/V > 0.7, Zr > 275 ppm, Nb+Y+Hf+Ta > 85 ppm, Sc/TiO<sub>2</sub> > 30. BW, Bore Well; CH, Copper Hills; D, Dalgara; GG, Golden Grove; H, Hollandaire; Ja, Jaguar; Ju, Jundee; M, Melita; N, Norseman; Q, Quinns; SW, Spring Well; W, Windimurra; WR, Weld Range; Y, Youanmi; Y-TH, Yamarna/Tobin Hill**



**Figure 34.** Contoured immobile element ratios for felsic and intermediate volcanic and granitic rocks from the northern Youanmi Terrane, Yilgarn Craton (using the simple prediction Kriging method in ArcGIS). Areas of prospective crust are characterized by: a) low Zr/Y; and b) Th/Yb (indicative of shallow crustal melting and elevated crustal heat flux). Extent of map shown in Figure 33h



**Figure 35.** Contoured La/Yb ratios for felsic and intermediate volcanic and granitic rocks from the central Eastern Goldfields Superterrane (using the simple prediction Kriging method in ArcGIS). Areas of prospective crust are characterized by low La/Yb (indicative of shallow crustal melting and elevated crustal heat flux): a) blue region within dashed white line is area of highest prospectivity, broadly equivalent to the VMS prospective Kurnalpi rift zone; b) showing sample points and base metal prospects. Extent of map shown in Figure 33h

Base metal mineralization is apparently restricted to the possibly older sequences, with the Balingup 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 (GSWA, 2015b). No base metal occurrences have been identified in the younger Saddleback and Moranup greenstone belts (GSWA, 2015b).

To date, no significant VMS occurrences have been observed in the Narryer Terrane.

## Lithological associations

Most VMS occurrences in the Yilgarn Craton are associated with substantially bimodal volcanic complexes (basalt and rhyolite > andesite) near a major shift in the dominant magma type and episodes of volcanic quiescence. VMS mineralization is typically associated with a switch from mafic- to felsic-dominated activity, or where felsic volcanic rocks suddenly appear in mafic-dominated sequences. Episodes of volcanic quiescence are represented by black shale, chert or banded iron-formation. These mixed, VMS-prospective sequences also include turbiditic felsic volcanoclastic rocks, which may be debris flows associated with felsic dome complexes, and andesites (e.g. Jaguar, Hollandaire, King and Golden Grove). Hangingwall rocks can include rift-related mafic flows (e.g. Jaguar, Teutonic Bore).

Major shifts in the chemistry of magmatism just prior to VMS mineralization are a common feature of many Noranda-type VMS camps worldwide (Galley et al., 2007; Piercey, 2011). VMS deposits are typically associated with felsic strata, despite basalt being the dominant rock type in many bimodal-mafic districts. In the Talling greenstone belt, VMS mineralization is hosted in felsic schist close to the contact with underlying mafic volcanic rocks over a strike length of about 30 km. At Mount Gibson, although the footwall succession is dominated by tholeiitic mafic rocks (including some with komatiitic components), VMS mineralization occurs in the volcanic 'mixed mine sequence' where quartz-feldspar-porphyratic units first appear in the stratigraphy. The Quinns deposits in the Norie Group (e.g. Austin) also show this association, with mineralization within a mixed volcanic succession which separates a mafic-dominated footwall succession from overlying felsic volcanic rocks. Similar situations are observed at Just Desserts, Hollandaire, Erayinia, Jaguar, Wheatley, Wongan Hills and Chunderloo (see 'VMS occurrences in the Yilgarn Craton'). Felsic volcanic rocks at Narndee, Windimurra and Manindi directly overlie large layered gabbroic complexes, again highlighting a major shift in the geodynamic environment from a mafic-dominated environment (Murrouli Basalt) to one characterized by felsic magmatism (Yaloginda Formation).

The association between VMS mineralization and periods of volcanic quiescence in the Yilgarn Craton is characteristic of most deposits. However, the association with black (carbonaceous) shale appears to be largely

restricted to VMS-bearing sequences that formed after c. 2800 Ma. At Golden Grove, hydrothermal cherts and siltstones are the only fine-grained sedimentary rocks present (Clifford 1992) and they are not directly associated with mineralization. At Weld Range, VMS mineralization is associated with chert and jasper beds within finely laminated volcanoclastic rocks (Guilliamse, 2014). No association with fine-grained sedimentary rocks has been reported from the Talling greenstone belt. At Mount Gibson, minor interflow sedimentary rocks in the hangingwall sequence (associated with quartz andesites) consist of ferruginous chert (Yeats et al., 2008). Like the >2900 Ma deposits, the 2818–2813 Ma VMS deposits are predominantly associated with chert or banded iron-formation. At Manindi, semi-continuous horizons of gahnite-bearing, quartz-rich rock may represent recrystallized chert or banded iron-formation (Cornelius and Smith, 2004). At Narndee, gossans are stratabound within a succession of felsic volcanic rocks and are associated with chert and banded iron-formation (Marston, 1979). The Just Desserts deposit lies within a sequence of talc-altered basaltic hyaloclastites and calc-alkaline basaltic rocks associated with interbedded chert horizons (Hassan, 2014) and at Chunderloo, VMS mineralization forms a stratabound goethite-chrysocolla-malachite-azurite-cuprite-quartz horizon (Marston, 1979).

For the <2800 Ma VMS occurrences, a close spatial and temporal association between mineralization and carbonaceous shale has been recognized at Wattagee Well, Mount Alfred, Jaguar, Teutonic Bore, Bentley, Gum Creek, Leonora, Anaconda (shale type unknown), Erayinia (associated with massive pyrite, east of Claypan Fault), King, Nimbus and Rungine. These shale units typically overlie and/or host VMS mineralization. Mineralization at Copper Bore is also associated with a package of graphitic shales, although the age of the deposit is not well constrained.

The recognition of carbonaceous shale may have important implications for the formation and preservation of VMS deposits on the seafloor. Anoxic seawater provides the opportunity for an unlimited supply of reduced sulfur to fix metals during the formation of effusive VMS deposits and the lack of oxygenated bottom waters prevents sulfide oxidation. Most of the giant Phanerozoic VMS deposits (e.g. Bathurst Mining Camp, Iberian Pyrite Belt, Mount Read Belt) and SEDEX deposits (e.g. Red Dog, Howards Pass, Anvil District) formed during periods of global anoxia in the Late Cambrian, Middle Ordovician, Late Ordovician – Early Silurian, and Late Devonian – Early Mississippian (Goodfellow, 2007). A clear exception to this is in the Urals (Herrington et al., 2005), where giant and supergiant deposits are associated with large and long-lived hydrothermal systems. Alternately, formation of VMS deposits in siliciclastic environments as replacement orebodies immediately protects sulfides from any potential oxygenated waters (e.g. Duck Pond, Newfoundland). In this instance, thick successions of argillaceous rocks may help to drive hydrothermal circulation by acting as a cap on the system, facilitating lateral fluid flow and the development of higher temperatures. Few VMS deposits from the Yilgarn Craton have been described in detail and it is unclear whether most formed from effusive or

replacement processes. However, the deposits in the two largest camps (Golden Grove and Teutonic Bore) clearly formed primarily through replacement processes (e.g. Sharpe and Gemmell, 2001; Belford, 2010). Recent studies on the smaller Nimbus (Hollis et al., in press), King (Hollis et al., 2016) and Hollandaire (Hayman et al., 2015) deposits also suggest mineralization was predominantly seafloor formed by replacement.

The recognition of andesites in the Jaguar stratigraphy by Ellis (2004) and Belford (2010) was an important discovery for future Yilgarn VMS exploration. Although many areas characterized by bimodal volcanic complexes are considered prospective for VMS mineralization, andesites are abundant around the most VMS-prospective successions. At Jaguar, there are andesites both in the stratigraphic hangingwall and footwall to the mineralization (Belford, 2010). At Mount Gibson, quartz andesites have been recognized in the hangingwall of the VMS-bearing 'mixed mine sequence' (Yeats et al., 1998). At Golden Grove, there are minor andesites in the Golden Grove Formation (Sharpe and Gemmell, 2002; Fig. 7). Andesitic rocks have also been recognized in association with synvolcanic copper–gold mineralization in the Ravensthorpe greenstone belt (e.g. Marston, 1979), at King (Hollis et al., 2016), The Cup (Gateway Mining, 2012), Hollandaire (Hayman et al., 2015) and potentially also around Narndee (Wingate et al., 2012c). The recognition of andesites in lithologically mixed successions associated with other Yilgarn VMS deposits is considered likely.

Mafic intrusive rocks are also commonly associated with VMS mineralization in the Yilgarn Craton, although they are mostly late. Mafic intrusive rocks have been reported at Golden Grove, Copper Bore (gabbro sills), Weld Range (dolerite and gabbro sills), Anaconda (dunite and gabbro sills), Wattagee Well (gabbro sills), Nimbus (basaltic sills) and Jaguar – Teutonic Bore – Bentley (dolerite and gabbro sills) (see 'VMS occurrences in the Yilgarn Craton'). At Jaguar, hangingwall mafic rocks and crosscutting intrusive rocks (Fig. 20) are geochemically distinct from footwall mafic rocks and are characterized by higher Y and lower La/Yb, La/Sm and Zr/Y (Belford, 2010).

The occurrence of rift-related mafic lavas in the hangingwall of VMS deposits (and crosscutting intrusive rocks of similar composition) is a common feature for most VMS deposits worldwide (see Piercey, 2011). In bimodal–mafic and mafic–siliciclastic sequences, which host Noranda-type and Besshi-type VMS deposits, respectively, hangingwall mafic rocks are commonly characterized by icelandite ([Fe,Ti]-enriched island-arc tholeiite), back-arc basin basalts and/or mid-ocean ridge basalts (MORB). In more evolved settings (e.g. bimodal–felsic and felsic–siliciclastic sequences), alkaline basalts are common in the hangingwall of VMS deposits (e.g. eMORB, ocean island basalts), which can be overlain by MORB representing the transition to seafloor spreading. It is unclear whether the mafic volcanic rocks of the Cattle Well Formation at Golden Grove are geochemically distinct from mafic rocks of the Gossan Valley Formation that preceded mineralization.

The close association between VMS mineralization and felsic volcanoclastic successions is also typical of many VMS camps worldwide (e.g. Abitibi greenstone belt). Although most VMS deposits are associated with felsic rocks, coherent felsic flows and domes are not suitable host rocks for the formation of large orebodies. VMS deposits hosted by flows are likely to be small due to: 1) problems associated with forming large deposits by replacement processes in coherent rocks under the seafloor; and 2) problems associated with effusive processes on the seafloor, such as bottom-water oxygenation, redeposition of sulfides, and coeval volcanic activity. However, the products of explosive felsic volcanism, especially those redeposited by mass-flow processes, provide suitable pathways for sub-seafloor hydrothermal fluids (e.g. Okinawa Trough; Takai et al., 2012). Most large-tonnage VMS deposits worldwide formed through replacement processes in volcanoclastic units (e.g. Bathurst, Iberian Pyrite Belt).

In the Yilgarn Craton, the Golden Grove Formation is characterized by the products of distal explosive felsic volcanism, which have been redeposited by successive mass-flow processes. The Scuddles Formation, which directly overlies the VMS-bearing Golden Grove Formation, consists of quartz–feldspar–phyric rhyodacite, which is in turn overlain and intruded by feldspar–quartz–phyric dacite. These units are interpreted to be an intrusive/extrusive dacite dome that overlies its discordant volcanic feeder (see 'VMS occurrences in the Yilgarn Craton'). The large tonnage of the Golden Grove camp may be explained by replacement-style mineralization in a thick sequence of felsic volcanoclastic strata sealed by overlying coherent lavas with or without impermeable sedimentary rocks.

## Petrochemistry of VMS-associated felsic (and intermediate) rocks

VMS-bearing units in the Yilgarn Craton (e.g. Golden Grove, Jaguar, Hollandaire, Dalgarranga, Youanmi, and Gum Creek) are similar to those of the VMS-rich camps of the Abitibi greenstone belt and the Pilbara Craton of Western Australia. VMS-associated and prospective rocks are characterized by: high-SiO<sub>2</sub> (in unaltered and altered rocks); tholeiitic to transitional Zr/Y and La/Yb values; FII to dominantly FIII characteristics; flattish REE profiles (Dy/Yb<sub>CN</sub> ratios ~1 and La/Sm<sub>CN</sub> <3); high HFSE concentrations; high Sc/TiO<sub>2</sub> and Sc/V; and low Th/Yb (Th/Yb <2 and Th >5ppm). Chondrite-normalized REE profiles for VMS-associated, c. 2815 Ma felsic rocks of the Youanmi Terrane are flat (Fig. 29). Other VMS-bearing units are characterized by slight LREE enrichment (La/Sm<sub>CN</sub> <3) and flat HREE profiles (Dy/Yb<sub>CN</sub> ratios ~1 or less). HREE concentrations are higher in VMS-associated felsic rocks than unprospective units. In some instances, Dy/Yb<sub>CN</sub> values <1 and slight LREE-enrichment (La/Sm<sub>CN</sub> <3) produce weakly U-shaped chondrite-normalized REE profiles (e.g. Golden Grove formation). For the REE, the best discrimination is provided by Dy/Yb<sub>CN</sub> ratios, as HREE profiles are



typically flat and Yb concentrations are often higher in VMS associated felsic rocks. La/Yb<sub>CN</sub> ratios of felsic rocks associated with VMS mineralization are also lower than unprospective units (due to LREE-enrichment over the HREE).

Negative Eu anomalies are present in a number of petrochemically prospective felsic rocks in the Yilgarn Craton, and are well developed at Windimurra, Hollandaire, Jaguar, Melita, Scuddles, Weld Range and Gossan Hill. Such anomalies have been classically viewed as a strong indicator of the 'fertility' of felsic rocks to host VMS mineralization in unaltered rocks (e.g. Leshner et al., 1986) due to extensive fractionation of plagioclase at shallow crustal levels. However, as noted by several authors, the redox characteristics of Eu mean it is mobile during hydrothermal activity (Sverksensky 1984; Mitra et al., 1994). Positive Eu anomalies have been demonstrated in the Heath Steele Belt of the Bathurst Mining Camp to provide a good measure of the hydrothermal component of exhalative rocks and represent a powerful geochemical vector towards sites of VMS mineralization in prospective sequences (Miller et al., 2001; Peter, 2004). Pronounced positive Eu anomalies have also been reported at Jaguar and Scuddles in the mineralized zone, and in basaltic rocks that host massive sulfides at Teutonic Bore (CSIRO, unpublished data).

Known VMS 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 includes both VMS-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 Jeedamyra). Felsic volcanic complexes at Melita and Teutonic Bore were described as having elevated concentrations of SiO<sub>2</sub>, HFSE and Y (i.e. A-type, FIII 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 has demonstrated the Teutonic Bore volcanic complex is not in fact bimodal as andesitic rocks are present in the hangingwall of mineralization at Teutonic Bore, Jaguar and Bentley (e.g. Belford, 2010). New data reported here suggest that both petrochemically favourable and unprospective felsic rocks occur at Spring Well and Melita, although the former is characterized by slightly lower REE concentrations.

In the Youanmi Terrane, in addition to areas associated with VMS mineralization (e.g. Golden Grove, Hollandaire, Mount Gibson, Copper Hills, Quinns, Emily Well, Gum Creek, Jillewarra, Gullewa), petrochemically prospective samples have been identified from Abbotts, Big Bell, Koolanooka, Lake Weelhamby, west of Quinns, and Marda. Although samples from Abbotts are largely unprospective (e.g. FI to FII affinity; low HFSE), one sample from southwest of Abbotts shows a flat REE profile, negative Eu anomaly, and tholeiitic Zr/Y ratio (FIV affinity). Chondrite-normalized REE profiles for

unprospective samples are similar to those from Golden Grove, although HREE concentrations are lower and some display steep LREE profiles. Minor base metal occurrences have been reported from the Conroy area (e.g. Conroy Pb; GSWA, 2015b), although the style of mineralization is not known. Felsic tuffaceous rocks from the Abbotts greenstone belt have yielded ages between c. 2734 and 2750 Ma (Wang 1998), indicating they are part of the VMS-bearing Greensleeves Formation (Van Kranendonk et al., 2013).

One sample from Big Bell showed significantly higher Y (38 ppm), V (385 ppm), Ni (46 ppm), Cr (22 ppm), Ba (1694 ppm) and Mo (30 ppm), and may indicate the presence of VMS-prospective felsic rocks in this area but there are no reliable REE data. Peraluminous schists at Big Bell may be consistent with synvolcanic alteration of a VMS-epithermal hybrid system. Sheared felsic volcanic rocks from the Big Bell gold mine have an age of  $2737 \pm 4$  Ma (Mueller et al., 1996), placing them within the VMS-bearing Greensleeves Formation.

Felsic rocks from west of Quinns also display chondrite-normalized REE profiles similar to Group II felsic rocks of Abitibi and the VMS-bearing Golden Grove Formation but are generally displaced to lower REE concentrations. They have low HFSE concentrations, high Th/Yb ratios and FII to FIIIa affinities. A sample with high Y (56 ppm) may be of interest. Positive, prominent Eu anomalies in some samples, and broad U-shaped REE profiles in some samples (similar to Golden Grove and Ravensthorpe east), indicate a need for further sampling in the area.

Samples from the c. 2730 Ma Marda Complex predominantly have unprospective FI to FII characteristics, and relatively steep HREE profiles, although some show strong HFSE enrichment. Recognized VMS mineralization in the Marda area (Fig. 1b; Copper Bore and Marda base metal occurrences; GSWA, 2015b) is restricted to the older greenstone sequence which unconformably underlies the Marda Complex and contemporaneous clastic sedimentary rocks of the Diemals Formation (Chen et al., 2003). The presence of HFSE-enriched synvolcanic granite nearby (e.g. Butcher Bird Monzogranite; see following section) and petrochemically prospective rocks suggest the Marda Complex is also prospective for VMS mineralization. However, if the Marda Complex was erupted subaerially or at very shallow water depths, it should be considered unprospective.

In the Eastern Goldfields Superterrane, VMS mineralization at Anaconda (Murrin Murrin) occurs in pyritic, feldspathic wacke, siltstone and shale, interpreted as distal deposits to the Welcome Well Complex to the northwest (Hallberg, 1985). Although the Welcome Well Complex has not historically been considered to be petrochemically prospective, the VMS prospectivity of the region is worthy of further study. Samples of interest identified from Bore Well (southeast of Murrin Murrin) are characterized by similar REE profiles to those at Jaguar, albeit displaced to lower REE concentrations and with higher La/Sm<sub>CN</sub> values. Some samples have moderately high HFSE concentrations, together with flat HREE profiles (Dy/Yb<sub>CN</sub> 1.0 – 1.1) and pronounced negative Eu anomalies.

Felsic rocks geochemically similar to those that host VMS mineralization at Abitibi and Jaguar have been identified near Tobin Hill in the Yamarna Terrane (Figs 5, 24b). A date of  $2677 \pm 7$  Ma on rhyolite from this area (Pawley et al., 2012) suggests the sequence is similar in age to the volcanic complexes exposed at Melita, King and Teutonic Bore (albeit slightly younger than the latter). Felsic rocks that display chondrite-normalized REE profiles similar to the Jaguar andesites (e.g. Bulong and Mount Venn) may be of interest. Other samples of interest were recognized from Green Dam, Harbour Lights, Leonora and Norseman.

In the Eastern Goldfields Superterrane, large volumes of HFSE-enriched intrusive rocks occur in the northern Kalgoorlie Terrane. Together with low Zr/Y and La/Yb ratios for associated felsic volcanics at Jundee and Yandal, this suggests these areas may be of interest for VMS exploration. One sample from a drillhole at Jundee has an Additive Index value of 7, due to low Zr/Y, La/Yb<sub>CN</sub> and Th/Yb, and high HFSE, Sc/V, Sc/TiO<sub>2</sub> and Yb<sub>CN</sub>. In the Agnew–Wiluna belt of the northern Kalgoorlie Terrane, bimodal volcanism is characterized by felsic volcanic and volcanoclastic sequences emplaced coevally with large komatiitic sills. Units such as the Mount Keith dacite host barren, pyrite-rich hydrothermal massive sulfide lenses for about 80 km between Albion Downs and Perseverance (Fiorentini et al., 2012). These lenses are regarded as significant in the formation of world-class Ni-sulfide mineralization at sites such as Mount Keith (Fiorentini et al., 2012). At Jericho and South Jericho (Albion Downs area), komatiite-hosted basal Ni-sulfides truncate a dacite-hosted Cu- and Zn-bearing, VMS-style stringer–stockwork zone (Fiorentini et al., 2012), demonstrating at least some areas are associated with base metals. The prospectivity of the Kambalda Sequence was further highlighted by recent SHRIMP geochronology from the Ag–Zn(–Au) Nimbus deposit (Hollis et al., in press).

## Association with synvolcanic HFSE-enriched granitic intrusive rocks and large mafic–ultramafic igneous complexes

Synvolcanic intrusions are integral to VMS belts and commonly show a clear spatial association with mineralization (Sangster, 1980). They may actively contribute metals, fluids and volatiles to some VMS systems (Piercey, 2011). Galley (2003) suggested VMS exploration should be focused in the coeval volcanic rocks up to three kilometres up-section of large subvolcanic intrusions. Although synvolcanic granitic intrusive rocks may not necessarily be the main drivers of hydrothermal circulation, they record the presence of deeper-seated heat in the region (e.g. basaltic underplating at 3–10 km depth; Piercey, 2011). Synvolcanic intrusions may also utilize the same deep-seated crustal pathways that were conducive to hydrothermal circulation, and thus their distribution may reflect the thermal corridor of the belt (e.g. Galley, 2003).

Synvolcanic suites of gabbro–diorite–tonalite–trondhjemite have been recognized from a number of VMS mining camps worldwide (e.g. Archean Panorama,

Noranda, Sturgeon Lake, and Snow Lake; Franklin et al., 2005). In primitive arc successions, composite synvolcanic intrusions typically consist of diorite–tonalite–trondhjemite intrusions with tholeiitic (low Zr/Y, La/Yb) signatures, and are associated with Cu(–Au) or Cu–Zn VMS deposits (Galley, 2003). By contrast, the rifting of thicker arc crust in more evolved successions results in partial melting at higher levels and calc-alkalic composite intrusions, commonly of granodioritic to granitic composition. These intrusions are typically present in camps that host polymetallic VMS deposits (Galley, 2003).

In the Yilgarn Craton, data discussed in this study suggest that a combination of crustal rifting, shallow partial melting of tholeiitic basaltic rocks, and magma fractionation led to the formation of the VMS-prospective, tholeiitic and HFSE-enriched felsic rocks during several periods. It is likely that the HFSE-enriched granitic intrusions are petrogenetically related to these felsic rocks, to which they show a clear spatial and temporal association (Figs 3, 4, 11, 18; Hollis et al., 2015).

## Youanmi Terrane

In the Youanmi Terrane, there is a clear spatial and temporal association between petrochemically prospective felsic rocks and HFSE-enriched granitic intrusions (Champion and Cassidy, 2002b) for each of the four main periods of VMS mineralization (Fig. 3). The geochemical characteristics of the HFSE-enriched granitic suites mentioned below are discussed in detail by Ivanic et al. (2012). The timing of VMS mineralization in the Youanmi Terrane also shows a clear association with the emplacement of large mafic igneous complexes (Fig. 11).

In older (>2900 Ma) greenstone belts, HFSE-enriched intrusions are represented by an unnamed suite, constrained in age by a SHRIMP U–Pb zircon date of c. 2935 Ma on the Mount Gibson monzogranite (Fig. 3; Yeats et al., 1996).

Following a major plume event at 2.82 Ga, the Mount Kenneth Suite was emplaced at c. 2815 Ma, coeval with large 2815–2800 Ma mafic–ultramafic igneous complexes of the central Youanmi Terrane (Boodanoo and Meeline Suites). The Mount Kenneth Suite is the intrusive equivalent of the Yaloginda Formation, which hosts VMS mineralization at sites such as Quinns, Narndee, Youanmi and Windimurra (Ivanic et al., 2012). SHRIMP U–Pb zircon geochronology on supracrustal sequences at Windimurra ( $2813 \pm 3$  Ma; Nelson, 2001b) and Youanmi ( $2814 \pm 14$  Ma; Nelson, 2002) have the same age as VMS-bearing felsic rocks of the Yaloginda Formation. Andesitic rocks at Narndee, which are intruded by the Narndee Igneous Complex, have a similar age ( $2818 \pm 3$  Ma; Wingate et al., 2012c). A SHRIMP U–Pb zircon date of  $2813 \pm 3$  Ma for the Courlbarrloo Tonalite (Fletcher and McNaughton, 2002), east of Youanmi (Fig. 11), constrains the age of the Mount Kenneth Suite.

The Boodanoo and Meeline Suites in the central Youanmi Terrane provided a major crustal heat source conducive to the formation of VMS deposits. Pyroxene geobarometry from gabbros of the Windimurra Igneous Complex suggest



it was emplaced at mid-crustal depth ( $\leq 400$  MPa; Ahmat, 1986). The Windimurra Igneous Complex has a true thickness of about six kilometres and covers an area of  $2500 \text{ km}^2$  (Ivanic et al., 2010). Pressure estimates from the younger and smaller Narndee Igneous Complex suggest it was emplaced at 3–10 km depth (100–300 MPa; Scowen, 1991). It is likely that 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 Sm–Nd  $T_{2DM}$  model ages (Fig. 2a; Ivanic et al., 2010; the ‘Cue Zone’ of Huston et al., 2014). Pre-existing structural weaknesses allowed magma to rise to relatively shallow crustal levels (Ivanic et al., 2010; Hollis et al., 2015). The emplacement of these large intrusions at shallow depths provided sufficient heat for hydrothermal circulation in the upper crust.

The third major period of VMS mineralization in the Youanmi Terrane is hosted in the Greensleeves Formation. The HFSE-enriched Peter Well Granodiorite (Eelya Suite), 28 km northeast of Cue, has a SHRIMP U–Pb zircon age of  $2747 \pm 6$  Ma (Wang, 1998; Van Kranendonk et al., 2013). Similar dates have been obtained from closely associated monzogranite ( $2749 \pm 6$  Ma; Wang, 1998) and biotite granite ( $2759 \pm 3$  Ma; Wingate et al., 2010b). This timing is consistent with a crystallization age of a rhyolite from near Hollandaire ( $2746 \pm 4$  Ma; Wingate et al., 2012a). The overlap in dates between the Cullculli and Eelya Suites is consistent with both TTG-like and FIII type felsic rocks in the Greensleeves Formation. The former are the extrusive equivalents of the Cullculli Suite, whereas the latter are the extrusive equivalents of the Eelya Suite.

VMS mineralization in the 2735–2700 Ma Glen Group in the Gum Creek greenstone belt (Fig. 16) is associated with felsic volcanic rocks and carbonaceous sedimentary rocks. Felsic volcanic rocks near the Bevan base metal occurrence have SHRIMP U–Pb zircon age of  $2722 \pm 6$  Ma (Bodorkos et al., 2006). A coeval monzogranite ( $2722 \pm 7$  Ma; Wang et al., 1998) appears to be spatially and temporally associated with VMS mineralization in the Gum Creek greenstone belt. The c. 2730 Ma Butcher Bird Monzogranite (Nelson, 2001a) at Marda is similar in age to volcanic rocks of the Marda Complex and is HFSE enriched (Morris and Kirkland, 2014). The emplacement of thick, differentiated, mafic–ultramafic sills of the Yalgowra Suite into shallow levels of the crust across the Youanmi Terrane at this time may have driven hydrothermal circulation. The cumulative thickness of the Yalgowra Suite is about one kilometre (Wyche et al., 2014) and its age is constrained by U–Pb zircon dates of  $2735 \pm 5$  Ma,  $2719 \pm 6$  Ma, and  $2711 \pm 2$  Ma (Ivanic et al., 2010).

## Eastern Goldfields Superterrane

Cassidy and Champion (2002) and Champion and Cassidy (2002a) have identified HFSE-enriched granitic rocks in the Eastern Goldfields Superterrane in the vicinity of the Teutonic Bore – Jaguar–Bentley, Anaconda and Jungle Pool base metal occurrences (Fig. 18). They appear to be most abundant in the Kurnalpi Terrane but the dataset is

incomplete. HFSE-enriched intrusive rocks range in age from  $>2720$  to 2650 Ma and include:

1. c. 2693 Ma granite north of Teutonic Bore – Jaguar–Bentley in the Kurnalpi Terrane (Geoscience Australia sample 96969014, Fletcher et al., 2001)
2. c. 2658 Ma granodiorite at Weebo north of Teutonic Bore (Nelson, 1997a)
3. c. 2703 Ma in the Kurnalpi Terrane east of Anaconda (Geoscience Australia samples 2000969003, 2000969004, Fletcher et al., 2001)
4. c. 2680 Ma in the Kurnalpi Terrane near Jungle Pool (Dairy Monzogranite: Geoscience Australia sample 96969024 from Zone 51, MGA 35327E 6754664N; DC Champion, Geoscience Australia, written comm., January 2013)
5. c. 2719 and 2710 Ma from southeast of Jungle Pool (GSWA 112177, Nelson, 1996; GSWA 142807, Nelson, 1997b).

Diagnostic features include the presence of amphibole and a combination of high FeO, MgO,  $\text{TiO}_2$ , Y and Zr, with low Rb, Pb, Sr and  $\text{Al}_2\text{O}_3$  (Czarnota et al., 2010).

In summary, the close temporal and spatial association of HFSE-enriched granitic rocks with VMS-bearing volcanic successions at Teutonic Bore – Jaguar–Bentley, Hollandaire, Anaconda, Windimurra, Narndee, Just Desserts, Jungle Pool, and in the Dalgaranga, Tallering, Twin Peaks, Ravensthorpe and Yalgoo–Singleton greenstone belts suggests that HFSE-enriched granitic rocks may be used to identify VMS prospective volcanic successions (see also discussion in Hollis et al., 2015; Hayman et al., 2015). In the Eastern Goldfields Superterrane, the most abundant HFSE-enriched volcanic rocks are in the Kurnalpi Terrane. The occurrence of HFSE-enriched granitic rocks in the northern part of the Kalgoorlie Terrane, to the east and southeast of Anaconda in Kurnalpi Terrane, and in the eastern Youanmi Terrane (Butcher Bird Monzogranite) suggests that these areas may also be prospective for VMS mineralization (Fig. 18).

## Conclusions

Prospective host sequences for VMS mineralization in the Yilgarn Craton can be identified through the presence of largely bimodal volcanic complexes, synvolcanic faults, HFSE-enriched synvolcanic intrusions, regional isotope variations indicative of rifting (e.g. Nb, Pb, Hf), and specific petrochemical signatures indicative of shallow crustal melting. Episodes of volcanic quiescence at or near the ore horizon — represented by chert, black shale or banded iron-formation — are a common feature of nearly all VMS occurrences in the Yilgarn Craton.

In the Youanmi Terrane, four distinct periods of economic mineralization have been recognized:

1.  $>2900$  Ma, associated with early bimodal–mafic greenstone belts (e.g. Golden Grove, Ravensthorpe, Tallering, Twin Peaks, Weld Range)

2. c. 2815 Ma, following a major plume event and coeval with the emplacement of large igneous complexes of the Boodanoo and Meeline suites at shallow levels in the crust across the northern Youanmi Terrane (e.g. Austin, Youanmi, Narndee, Windimurra)
3. 2760–2745 Ma, in areas of rift-related magmatism during deposition of the Greensleeves Formation (e.g. Hollandaire, Mount Mulcahy, Dalgaranga, Chesterfield, Conroy)
4. c. 2725 Ma, in the Gum Creek greenstone belt during a second major plume event, coeval with the emplacement of high-level sills of the Yalgowra Suite.

HFSE-enriched granitic intrusions are spatially and temporally associated with each of the episodes of VMS mineralization in the Youanmi Terrane.

In the Eastern Goldfields Superterrane, VMS mineralization is closely associated with HFSE-enriched synvolcanic intrusions, and is mainly restricted to areas of juvenile crust and bimodal complexes that formed between c. 2695 and 2680 Ma (e.g. Teutonic Bore, King, Jungle Pool). Exceptions include c. 2698 Ma komatiite-coeval felsic rocks at Anaconda and significantly older VMS occurrences in the Burtville Terrane around Duketon. In the South West Terrane, VMS mineralization is preferentially associated with >3.0 Ga greenstone sequences.

VMS-bearing and prospective felsic rocks in the Youanmi Terrane and Eastern Goldfields Superterrane are characterized by: low Zr/Y, La/Yb and Th/Yb ratios; high Sc/TiO<sub>2</sub>, Sc/V, HFSE and HREE contents; and flat HREE profiles. Felsic rocks overlying 2820–2800 Ma plume-related basalts and large igneous complexes of the Youanmi Terrane have flat chondrite-normalized REE profiles. Other VMS-bearing felsic rocks are characterized by slight LREE enrichment (La/Sm<sub>CN</sub> <3) and flat HREE profiles (Dy/Yb<sub>CN</sub> ≤1).

Petrochemically prospective felsic rocks have been recognized in several areas across the Yilgarn Craton, most of which are associated with base metal occurrences (e.g. Copper Hills, Dalgaranga, and Windimurra) or HFSE-enriched intrusions (e.g. Twin Peaks greenstone belt). Additional areas which appear to be prospective for VMS mineralization, based on the prospectivity parameters described in this report, include but are not limited to: Abbots, Big Bell, Gullewa, Lake Weelhamby, Koolanooka and Marda in the Youanmi Terrane; Bore Well in the Kurnalpi Terrane; and Tobin Hill in the Yamarna Terrane. Areas of prospective crust have been defined using Zr/Y, La/Yb and Th/Yb ratios that are broadly equivalent to the Cue and Kurnalpi rift zones.

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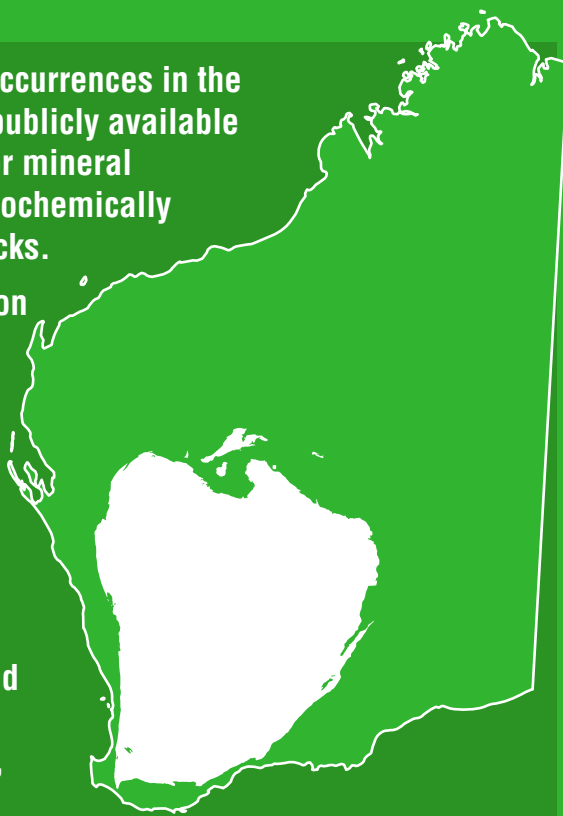
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This Report describes all known, major VMS occurrences in the Yilgarn Craton using published literature and publicly available company reports. Areas of potential interest for mineral exploration have been identified based on petrochemically favourable intermediate and felsic volcanic rocks.

Four distinct periods of economic mineralization and petrochemically favourable felsic rocks can be recognized in the Youanmi Terrane in the western part of the craton: 1) >2900 Ma, associated with early bimodal–mafic greenstone belts; 2) c. 2815 Ma, following a major plume event and coeval with the emplacement of large igneous complexes; 3) 2760–2745 Ma in areas of rift-related magmatism; and 4) c. 2725 Ma during a second major plume event. In the Eastern Goldfields Superterrane, in the eastern part of the craton, VMS mineralization is closely associated with HFSE-enriched synvolcanic intrusions, and is predominantly restricted to areas of juvenile crust and bimodal complexes that formed between 2700 and 2680 Ma. In the South West Terrane, in the southwestern part of the craton, VMS mineralization is preferentially associated with older, 3000–3200 Ma greenstone successions.



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

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