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Research paper

Besshi-type mineral systems in the Palaeoproterozoic Bryah Rift-Basin, Capricorn Orogen, Western Australia: Implications for tectonic setting and geodynamic evolution

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ABSTRACT

In this contribution we use VMS mineral systems in the Bryah rift-basin to constrain the tectonic setting of the widespread mafic and ultramafic magmatism that characterises the rift-basin in question. Two distinct, but temporally closely associated, lithostratigraphic sequences, Narracoota and Karalundi Formations, are discussed. The Karalundi Formation is the main host of VMS mineral systems in the region. The Karalundi Formation consists of turbiditic and immature clastic sediments, which are locally intercalated with basaltic hyaloclastites, dolerites and banded jaspilites. We propose that the basaltic hyaloclastites, dolerites and clastics and jaspilites rocks, form a distinct unit of the Karalundi Formation, named Noonyereena Member. The VMS mineral systems occur near the north-east trending Jenkin Fault and comprise the giant and world-class DeGrussa and the Red Bore deposits. The nature of these deposits and their intimate association with terrigenous clastic rocks and dominantly marine mafic volcanic and subvolcanic rocks, as well as the common development of peperitic margins, are considered indicative of a Besshi-type environment, similar to that of present-day Gulf of California. Our Re-Os age data from a primary pyrite yielded a mean model age of 2012 ± 48 Ma, which coincides (within error) with recent published Re-Os data (Hawke et al., 2015) and confirms the timing of the proposed geodynamic evolution. We propose a geodynamic model that attempts to explain the presence of the Narracoota and Karalundi Formations as the result of mantle plume activity, which began with early uplift of continental crust with intraplate volcanism, followed by early stages of rifting with the deposition of the Karalundi Formation (and Noonyereena Member), which led to the formation of Besshi-type VMS deposits. With on-going mantle plume activity and early stages of continental separation, an oceanic plateau was formed and is now represented by mafic-ultramafic rocks of the Narracoota Formation.

1. Introduction

An important discovery of massive sulphides hosted in rocks of the Palaeoproterozoic Bryah Group (Capricorn Orogen, Western Australia; Cawood and Tyler, 2004), known as DeGrussa Project Cu-Au was announced by Sandfire Resources NL in mid-2009. The DeGrussa mineralisation is a massive sulphide mineral deposit, blanketed by high-grade supergene sulphide and oxide ore. The discovery drillhole intersected 78 m of massive sulphides grading 3.6% Cu and 3.8 g/t Ag. Two spectacular intersections announced in the Australian Stock Exchange (ASX) releases of July 2009 and September 2009, include 53 m at 17.3% Cu and 2.5 g/t Au and 25 m at 3.4% Cu, 3.4 g/t Au and 1.6% Zn, respectively.

This new and exciting discovery brought about a "rush" of ongoing exploration in the area. The Red Bore prospect, an occurrence 0.5 km southeast of DeGrussa, is hosted in mafic rocks and may also be a similar VMS. At Red Bore a drill intersection of 17 m at 11.7% Cu, 1.73 g/t Au was announced in 2011 (SEG Newsletter, Exploration Reviews 2011).

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The DeGrussa and Red Bore are controlled by the NE-trending Jenkin Fault. This fault is the main structure that marks the boundary between the Bryah-Yerrida basin and the Marymia Inlier, extending across the northeastern part of the Bryah Rift-Basin (Fig. 1).

The DeGrussa discovery elicited a re-appraisal of the tectonic setting and geodynamic evolution the Bryah Rift-Basin and the two important lithostratigraphic units: the Narracoota Formation and Karalundi Formation of the Bryah Group (Bryah Rift-Basin), as detailed below. This re-appraisal builds on previous work carried out during Geological Survey of Western Australia (GSWA) mapping program in the eastern part of the Capricorn Orogen, between 1994 and 2003 (Pirajno and Occhipinti, 2000; Pirajno et al., 2000, 2004; Pirajno, 2004a,b) and more recently an overview of DeGrussa reported in Johnson (2013, as contributed by the first author of this paper). An understanding of the geodynamic evolution of the Narracoota and Karalundi lithostratigraphic units is pivotal for conceptual genetic models that can account for the origin of the primary massive sulphide mineralisation in the Bryah Basin. The evidence presented herein is convincing to show that the DeGrussa deposit is related to a predominantly mafic igneous activity mostly contemporaneous with terrigenous clastic sedimentation, which began in a narrow rift system and later developed as oceanic seafloor spreading with both mafic and ultramafic rocks.

2. Regional geological setting

The Bryah Rift-Basin, as defined in Pirajno et al. (2000), is situated along the northern margin of the Archaean Yilgarn Craton and is one of the tectonic units of the Palaeoproterozoic Capricorn Orogen, situated between the Yilgarn Craton in the south and the Pilbara Craton in the north (inset of Fig. 1; Cawood and Tyler, 2004). The Capricorn Orogen is the result of collisional events between the Yilgarn and Pilbara cratons at 1830–1780 Ma (Cawood and Tyler, 2004; Johnson et al., 2012; Johnson, 2013). The collision events were followed by later intracratonic reactivation, during the amalgamation of the West Australian Craton with the North Australian Craton (Tyler, 2005), with renewed basin development and magmatism between ca. 1670 and 1620 Ma (Tyler et al., 1998). The main domains of the Capricorn Orogen include, from west to east, the Gascoyne Province, Edmund and Collier basins, Bryah Rift-Basin, Padbury Basin, Yerrida Basin and the Earaheedy Basin, collectively extending for about a 1000 km long belt. The Yerrida, Bryah and Padbury basins, and Earaheedy Basin, form a series of depositional centres that extend for about 700 km E–W along the southeastern margin of the Capricorn Orogen and the northern margin of the Yilgarn Craton, covering a total area of approximately 70,000 km^2 (Cawood and Tyler, 2004; Pirajno et al., 2004) (Fig. 1). The sedimentary record of these basins is linked to the uplift of plutonic and metamorphic rocks of the Yilgarn Craton and units of the Gascoyne Province and possibly other unexposed Palaeoproterozoic terranes (Pirajno et al., 2004; Martin et al., 2008; Pirajno et al., 2009; Sheppard et al., 2011). The Capricorn Orogen is part of world-wide phases of continental collisions associated with supercontinent assembly (Cawood and Tyler, 2004; Johnson, 2013).

3. Bryah Rift-Basin

The Bryah rift-basin contains the Bryah Group and its simplified geology and lithostratigraphy, including the available geochronological data, are shown in Figs. 1 and 2. The Bryah Group consists of four formations, from base to top: Karalundi, Narracoota, Ravelstone and Horseshoe (Fig. 2) (Pirajno and Occhipinti, 2000). The structural and metamorphic evolution of the Bryah Group was investigated by Occhipinti et al. (1998) and only a brief account is given here.

The deformation and metamorphism of the Bryah Group rocks are probably linked to compressional movements and possibly to

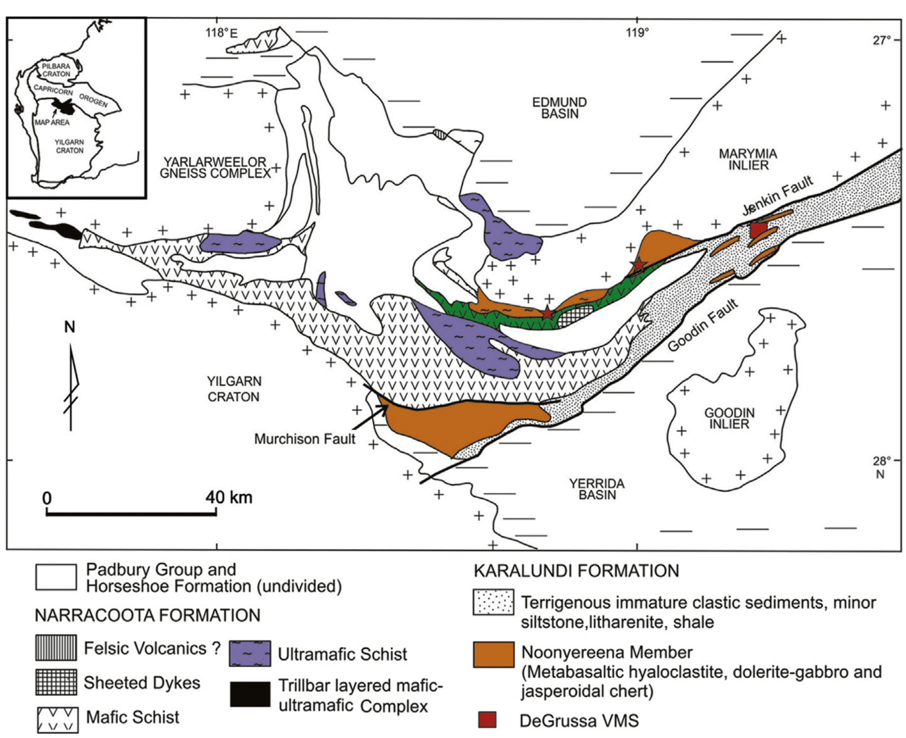

Figure 1. Simplified geology of the Bryah Basin and adjacent Yerrida Basin (modified after Pirajno et al., 2004).

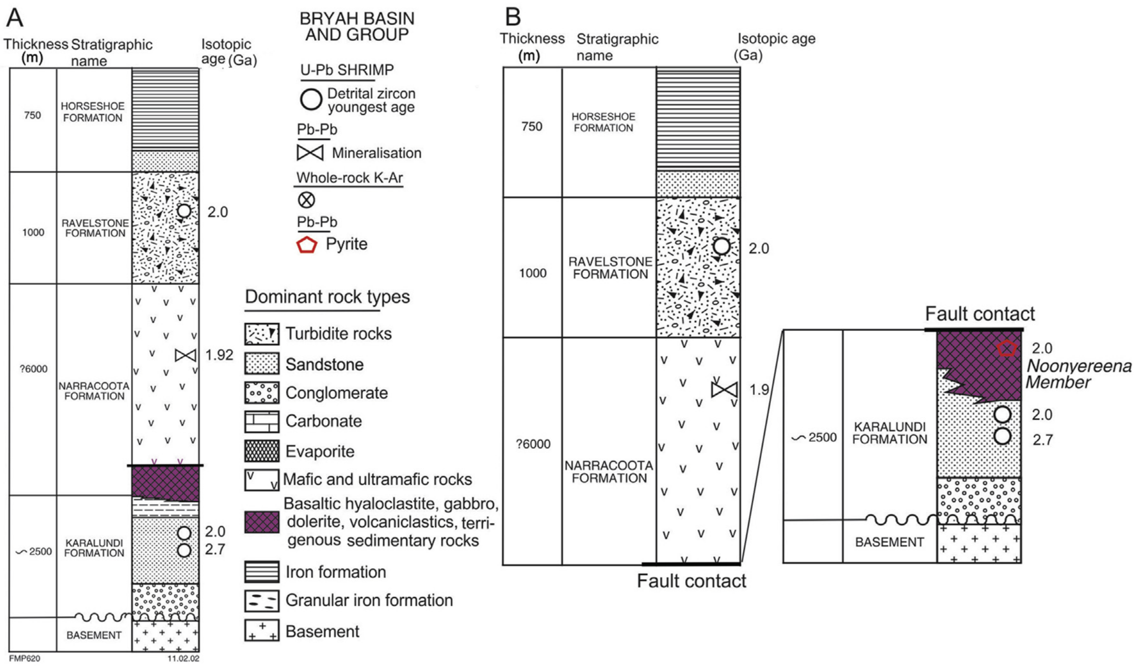

Figure 2. (A) Lithostratigraphy of the Bryah Group (after Pirajno et al., 2000, 2004); (B) revised lithostratigraphy with Noonyereena Member of the Karalundi Formation shown. Age data and methods used are also shown in both (A) and (B).

indentation from rigid Archaean blocks, eastward by the Yarlaweelor Gneiss Complex in the west and westward by the Marymia Inlier in the east (Fig. 1; Pirajno et al., 1995). At least four groups of structures (D_1–D_4) are recognized in the regional deformation of the Bryah Group and the reworked basement. The first phase of this deformation history (D_1–D_2) records the collision of the Gascoyne Province with the Yilgarn Craton during the Glenburgh Orogeny at about 1.96 Ga (Occhipinti et al., 1998, 2004; Sheppard et al., 2004). During the D_1 deformation event, subhorizontal high strain shear zones and tectonic interleaving occurred predominantly in the Narracoota volcanic succession and reworked Archaean basement. D_2 deformation event was characterised by N–S shortening, which resulted in E–W-trending upright folds and basement cored anticlines. The D_1–D_2 events were accompanied by prograde metamorphism. The D_3–D_4 phases record a phase of deformation that can be attributed to the Capricorn Orogeny, resulting in retrograde overprinting of the D_1–D_2 prograde metamorphic minerals, and were probably responsible for most of the orogenic lode gold deposits that occur in the Bryah Group and the overlying Padbury Group (Pirajno and Preston, 1998; Pirajno et al., 2000).

3.1. Karalundi and Narracoota formations

The Karalundi Formation has a maximum thickness of approximately 2500 m, consists of predominantly immature clastic and turbiditic sediments of rift-fill facies (Pirajno et al., 2000), forms the base of the Bryah Group, and outcrops in a northeasterly trending belt along the southeastern margin of the Bryah Basin (Fig. 1). The Karalundi Formation is in fault contact with the Mooloogool Group (Yerrida Basin; Pirajno et al., 2004) in the southeast and northeast, with the Narracoota Formation along the Murchison Fault in the south and the Marymia Inlier in the northeast (Fig. 1). It is important to note that tectonic interleaving between units of the Karalundi Formation and adjacent lithologies occurs along an interpreted thrust boundary between the Bryah and Yerrida groups (Goodin Fault), as well as along the margins of the Marymia Inlier (Jenkin Fault) (Fig. 1). The terrigenous immature clastic units of the Karalundi Formation contain angular quartz and lithic fragments set in a sericite–clay-rich matrix, suggestive of a high-energy environment. Detrital zircons from the basal Karalundi Formation yielded youngest ages of ca. 2.0 and 2.7 Ga (Fig. 2; Halilovic et al., 2004; Pirajno et al., 2004). The presence of both Archean and Palaeoproterozoic age zircon grains indicates diverse provenance, probably from the Yilgarn Craton for the Archean zircons, but the source for the zircons of Proterozoic age is problematic, although could be from a microcontinent associated with terranes of the Gascoyne Province (Pirajno et al., 2004). Sedimentary rocks of the Karalundi Formation are typically intercalated with basaltic hyaloclastite lavas, volcaniclastic rocks, dolerite and gabbro sills (Pirajno and Occhipinti, 2000; Pirajno et al., 2004), described below.

3.2. Noonyereena Member

The mafic rocks that are intercalated with the immature sedimentary units of the Karalundi Formation were previously considered as part of the Narracoota Formation (Pirajno et al., 2000). However, in view of the fact that the basalts, dolerites and gabbros are not only intercalated with the Karalundi sediments, but also display features indicating that their emplacement was mostly coeval (e.g. peperitic margins) with the deposition of the sediments in a narrow rift basin. Therefore it stands to reason that these mafic rocks should be considered as a separate lithostratigraphic sequence from the Narracoota Formation *sensu stricto*. For this reason they have been assigned to the newly established *Noonyereena Member* of the Karalundi Formation (Fig. 2). The name Noonyereena is derived from a hill, about 600 m a.s.l. situated in the Doolgunna 1:100,000 map sheet (Adamides, 1995) at AMG coordinates (721000E, 7168597N). The new stratigraphic name is officially lodged in the Geoscience Australia stratigraphic database (http://dbforms.ga.gov.au/pls/www/geodx.strat_units.sch_full?wher=stratno=29869).

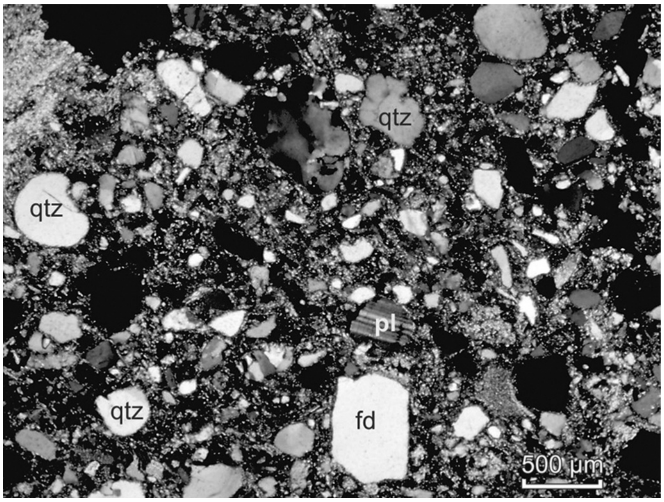

Figure 3. Photomicrograph in cross-polarised light showing an immature siltstone of the Karalundi Formation. qtz: quartz, fd: feldspar, pl: plagioclase, matrix is mostly quartz.

Basaltic hyaloclastites form a prominent outcrop area, partly covered by ferricrete and colluvium, south of the Murchison River in the southern part of the Bryah Basin (Fig. 1). These rocks are separated from the mafic and ultramafic schist of the Narracoota Formation by the Murchison Fault (Figs. 1 and 2), and in this area probably represent a substantial thickness of mafic lavas and subvolcanic intrusions. To the north, basaltic hyaloclastites occur along the southern margin of the Marymia Inlier (Fig. 1). Basaltic hyaloclastite rocks are intercalated with high-energy clastic sedimentary rocks (Fig. 3), dolerite and gabbro sills and volcaniclastic rocks. In contrast to rocks of the Narracoota Formation, within which they were previously included, the basaltic hyaloclastites are relatively undeformed and massive, except along the Jenkin Fault (Figs. 1 and 4D). The basaltic rocks commonly exhibit a characteristic brecciated or jigsaw-fit texture outlined by epidote, carbonate, prehnite, and quartz veining along cooling joints (Fig. 4A–C).

The term hyaloclastite denotes fragmentation due to quenching of lavas flowing in shallow water or erupting under an ice sheet. This results in non-explosive fracturing and disintegration of the quenched lavas (e.g. McPhie et al., 1993). As mentioned above, the basaltic hyaloclastites are generally undeformed and have a spilitic character. Spilites are basaltic rocks that are altered through metasomatic exchange with seawater, thereby increasing their sodium content (Amstutz, 1974). The hyaloclastites of the Noonyereena Member have normative albite from 13 to 23 wt.%, and Na_2O contents of up to 6 wt.%, and positive Eu anomalies (Eu/Eu* of 1.30–1.67), suggesting crustal contamination (Pirajno and Occhipinti, 2000). The hyaloclastites are commonly aphyric and composed mainly of acicular crystals of actinolite arranged in sheaves, together with epidote, minor carbonate, prehnite, quartz, and titanite, in a fine-grained groundmass of albite microlites, chlorite, and epidote. Coarse-grained equivalents display ophitic to subophitic textures. The presence of albite and high Na contents confirms interaction with seawater.

The basaltic hyaloclastites are in places intercalated with volcaniclastic rocks, which show a well-preserved eutaxitic or fragmental texture. In areas close to and along the Jenkin Fault, these fragmental rocks are strongly schistose, with flattened and stretched fragments of chlorite schist, quartz–chlorite schist with plagioclase phenocrysts, quartz–feldspar–amphibole rock, medium-grained plagioclase grains, and, more rarely, quartz crystals in a fine-grained matrix. Also part of the Noonyereena Member are volcanic proximal vent breccias, which are poorly exposed, but intersected in drill holes in the southern part of the Bryah Basin (McDonald, 1994; Pirajno and Occhipinti, 1998), as discussed below.

Volcaniclastics and volcanic breccias are present in at least three localities. The most important of these is 5 km north of the old Cashman mine, in the southern part of the Bryah rift-basin. Outcrops of volcanic breccia are also present at the Cashman mine area and 3 km west of the Peak Hill – Fortnum road junction. The nature of these angular, clast-supported, poorly sorted blocks of mafic volcanic material suggests that they are vent breccias. Volcanic breccia was intersected throughout 455 m of core in drillhole BD1 (Pirajno et al., 2000), drilled by North Exploration Ltd in 1993 (McDonald, 1994). This core intersection is briefly described below, summarized from Pirajno et al. (2000).

Drillhole BD1 was drilled to a depth of 520 m at an inclination of 70° towards the south, and intersected clays and gravels to a depth of 65 m, followed by weathered mafic volcanic breccias to 96 m.

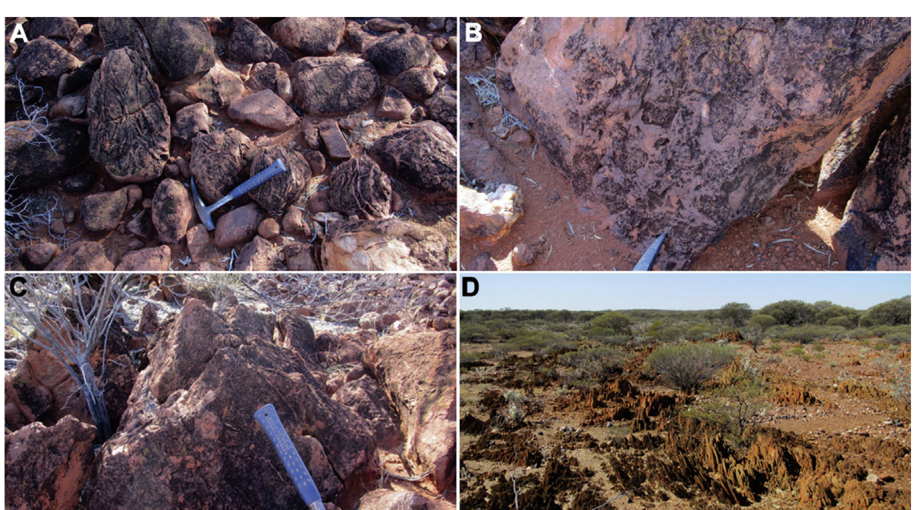

Figure 4. Field photographs showing key features of undeformed basaltic hyaloclastites of the Noonyereena Member (A, B, C, see text for details), D shows the same rocks deformed along the Jenkin Fault. The Noonyereena Member is newly established unit that consists of basaltic hyaloclastites, dolerite and gabbro sills, intercalated with high-energy clastic sedimentary rocks.

Figure 5. Volcanic breccia intersected in drill hole BD1; clasts are predominantly of basaltic rocks, while the matrix exhibits albitic alteration (after Pirajno et al., 2000).

Below this depth, to the end of the hole at 520 m, proximal vent-facies material consisting of angular blocks and clasts of basaltic lava, tuff, and chert were intersected (Fig. 5). Crude bedding is present locally, as are thin layers of laminated or cross-laminated cherty material. The hole bottomed in cross-laminated chert, which is interpreted as pyroclastic surge and tuff deposits. The basaltic rocks include fine-grained vesicular basalt, and feldspar-phyric and augite-phyric basalts. The phyric varieties are characterized by a microlite-rich feldspar matrix, clinopyroxene granules, interstitial glass and chlorite, and opaque minerals (titanite or rutile). The feldspar phenocrysts are selectively altered to sericite, whereas the augite phenocrysts are fresh and exhibit distinct zoning. Vesicles are infilled (from rim to core) by albite, epidote, chlorite, and calcite. Minor sulphide specks, mainly chalcopyrite, are locally present in the vesicular basalt. Hydraulic fracturing and veins of calcite, prehnite, quartz, and chlorite are abundant. One section between 200 and 360 m is characterized by nearly pervasive albitic alteration (sodium metasomatism), which imparts a pink to reddish colouration to veinlets and patches where the albite is present.

The fragmental mafic volcanic rocks in drillhole BD1 are interpreted to represent a proximal vent-facies volcanic breccia (Fig. 5). This vent-facies material coincides with prominent magnetic and Bouguer gravity anomalies (Pirajno et al., 1995). The magnetic anomaly, which may be related to the presence of magnetite in pyroxene basalt, has a well-defined northeasterly trending elliptical shape and could conceivably indicate the remnants of a major volcanic edifice. The gravity anomaly is at the centre of a large regional gravity high, which underlies most of the area occupied by the Narracoota Formation (Pirajno and Occhipinti, 1998).

Jasperoidal chert pods are locally present within rocks of the Noonyereena Member (Pirajno and Occhipinti, 1998). One of the largest pods outcrops in the southern part of the Bryah Basin. Windh (1992) investigated these chert pods, geochemically discriminated them on the basis of their Ni/Cr ratios, and distinguished jasperoidal syngenetic exhalative chert, silicified volcanic or sedimentary rocks, silicified shear zone rocks, and surface silicification. Several of these chert pods, such as those in the Narracoota Formation south of the Peak Hill Schist in northern Bryah, are quartz mylonites, probably silicified shear zone rocks, described by Windh (1992). However, those that occur in the Noonyereena Member show banding, resembling that of banded jaspilites (Fig. 6) which are interpreted as chemical precipitates deposited as distal facies of seafloor hydrothermal venting (Franklin et al., 2005). This jasperoidal material is reddish to grey coloured, massive to banded, and extensively quartz veined. The chert consists of very fine grained recrystallized quartz with equant to elongate polygonal–granoblastic textures, locally with a crystallographic preferred orientation. Minute grains of magnetite or pyrite, define trails parallel to the silica banding. Similar banded jaspilites, associated with VMS deposits, are present in the Abitibi greenstone belt in Canada (Mueller et al., 2008).

Figure 6. Outcrop of banded jaspilite in the Noonyereena Member.

The *Narracoota Formation* forms the bulk of the Bryah Group and includes metamorphosed peridotitic and high-Mg basalt, mafic volcaniclastic rocks, mafic intrusive rocks, mafic and ultramafic schist (Pirajno and Occhipinti, 1998; Pirajno et al., 2000). Mafic intrusive rocks cover a range of types from pyroxenite to gabbro. Rocks of the Narracoota Formation are folded and metamorphosed generally to mid-greenschist, but locally up to amphibolite facies, and as such the prefix "meta" is implied. The Narracoota Formation has an estimated maximum thickness of 6000 m (Gee and Grey, 1993; Pirajno and Occhipinti, 1998), however much of this thickness may be due to structural repetition, brought about by the four deformation periods mentioned above. The contact with the overlying Ravelstone Formation is locally disconformable (Pirajno and Occhipinti, 2000). In the north, regional structural relationships suggest that the Narracoota Formation is faulted against the Horseshoe Formation. Contacts between the Narracoota Formation and Padbury Group are also tectonic. The age of the Narracoota Formation is poorly constrained, with only a minimum age for given by a 1.92 Ga Pb-Pb isochron obtained from an inferred syngenetic pyrite (Fig. 2A; Windh, 1992).

Layered mafic and ultramafic rocks of the Trillbar Complex are considered part of the Narracoota Formation (Occhipinti and Myers, 1999). The Trillbar Complex was interpreted by Pirajno (2004b), as a fragment of a mantle plume-sourced oceanic plateau, which included the rest of the Narracoota Formation, later accreted onto the northern margin of the Yilgarn Craton. The geochemistry of the Narracoota Formation, although based on a limited dataset, was discussed by Pirajno and Occhipinti (1998, 2000). Rare earth elements (REE) abundances of mafic schist are moderate to low, with nearly flat chondrite-normalized patterns and weak negative Eu anomalies (Eu/Eu* of 0.31–0.43); ultramafic schist are light rare earth elements (LREE)-depleted $(La/Yb)_{CN}$. The chondrite-normalized REE patterns of the Narracoota Formation are effectively almost identical to those of oceanic plateaux (Kerr et al., 1998; Pirajno, 2004b).

4. Massive sulphide mineralisation close to the Jenkin fault system

As mentioned above the DeGrussa and Red Bore VMS systems occur in the northeastern sector of the Jenkin Fault (Fig. 1). They consist of massive and disseminated sulphides, generally capped by enriched supergene oxides and sulphide Au-dominated sulphide mineralisation. The descriptions that follow are based on regional and detailed field mapping, core logging and petrographic studies. It is important to note that the DeGrussa mineral system does not have a surface expression, therefore the mineralisation herein described is entirely based on diamond drilling core samples. On the other hand, the Red Bore prospect has an exposed gossan and a strong coincident magnetic anomaly, due to presence of massive and disseminated magnetite.

4.1. DeGrussa VMS deposit

The DeGrussa deposit is a mafic-siliclastic (Franklin et al., 2005) volcanogenic massive sulphide mineral system that was discovered by Sandfire Resources in April 2009. Mining of the DeGrussa deposit commenced in 2012 and as of 31st December 2014, 167,000 t of Cu and 98,000 oz Au had been produced. On 31st December 2014 the remaining resource (Taylor and Hastings, 2015) was estimated at 2.8 Mt of stockpiled oxide ore averaging 1.2% Cu and 1.0 g/t Au (contained metal of 33,000 t Cu and 80,000 oz Au) and an in-situ underground resource of 9.5 Mt grading 5.7% Cu and 2.0 g/t Au (contained metal of 546,000 t Cu and 616,000 oz Au).

DeGrussa comprises four spatially separated zones of massive sulphide mineralisation referred to as DeGrussa, Conductor 1, Conductor 4 and Conductor 5 (Fig. 7). In each of these zones, massive sulphide mineralisation occurs at one or more (up to six for Conductor 5) stratigraphic levels within a sequence of interbedded siltstone, sandstone and conglomerate thought to have been deposited by turbidity currents and density flows (Adamczyk, 2013).

The host sediments contain numerous basaltic sills exhibiting peperitic textures on both upper and lower contacts. This indicates that the sills were intruded into unlithified sediment. Massive sulphide mineralisation and associated minnesotaite-carbonate-chlorite-sulphide or chlorite-sulphide alteration has commonly replaced peperite textured portions of basalt-sediment contact zones (Adamczyk, 2013). In other portions of the deposit, breccias containing massive sulphide clasts, remnant chimney fragments and bedded sulphide rich sediments support the development of seafloor mounds (Hawke et al., 2015).

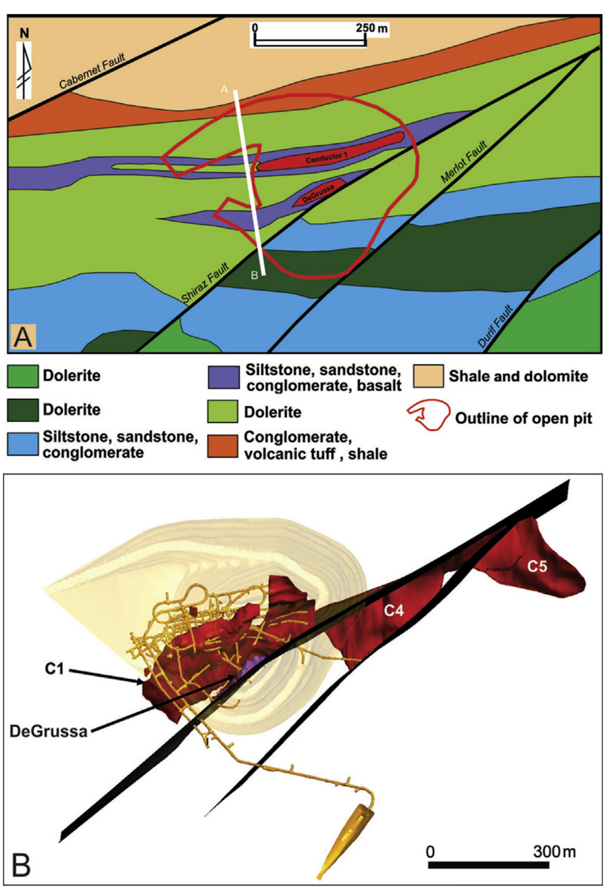

Figure 7. Plan view of the mine geology of DeGrussa and Conductor 1 (A) and 3D cross-section showing mine development, orebodies and faults (B). Figure courtesy of Paul Hilliard of Sandfire Resources Ltd.

The turbidite derived sediments have been intruded by dolerite sills that have similar chemistry to those of the basalts and are interpreted to have been derived from the same parent magma (Adamczyk, 2013). The dolerite sill immediately below the host unit (footwall dolerite) exhibits a peperite contact with the sediment, whereas the dolerite sills in the hanging-wall of the deposit have sharp contacts with chilled margins (Paul Hilliard, written comm., 2015). The DeGrussa orebody is considered to have originally been attached to the Conductor 1 orebody but is interpreted to have been separated from it by the intrusion of a post-mineralisation dolerite sill that intruded at a low-angle to lithological layering (Hawke et al., 2015).

Underlying the footwall dolerite is a sedimentary breccia, comprising poorly sorted, angular to sub-angular dolomite clasts, ranging from 4 cm to greater than 5 m in size, in a siltstone to sandstone matrix (Adamczyk, 2013).

The dolerite sills in the hanging-wall of the deposit have been dated (U-Pb zircon) at between 1991 $\pm$ 7 and 2003 $\pm$ 7 Ma (Hawke et al., 2015). Chilled margins and the lack of peperites indicate that these dolerites intruded into dry, partly lithified sediment. VMS mineralisation at DeGrussa occurred prior to the intrusion of these dolerites but after the basaltic sills that intruded wet, unlithified sediments at an earlier stage during the same magmatic event (Paul Hilliard, written comm., 2015). Hawke et al. (2015) undertook Re-Os dating of molybdenite in the DeGrussa orebody and reported ages of mineralisation ranging from 2027 $\pm$ 7 to 2011 $\pm$ 7 Ma. These ages coincides, within error, with the Re-Os age of primary pyrite of 2012 $\pm$ 8 Ma, reported in this paper (see below).

Subsequent to mineralisation and cessation of mafic volcanism the DeGrussa deposit was deformed during NNE–SSW directed compression and situated along the steeply south-dipping (60°–70°) northern limb of a shallow WSW plunging, upright syncline that developed during this event. Two significant faults have been mapped in the mine area, with estimated displacements of 500 and 80 m respectively. Pre-faulting reconstruction demonstrates that the Conductor 1/DeGrussa, as well as the Conductor 4 and Conductor 5 orebodies were originally all part of a single, continuous zone of mineralisation (Fig. 7) (Paul Hilliard, written comm., 2015).

Folding and faulting of the DeGrussa deposit is interpreted to have developed during the 1820–1770 Ma Capricorn Orogeny (Cawood and Tyler, 2004; Sheppard et al., 2005).

4.2. Red Bore

The Red Bore prospect owned and/or operated by Thundelarra Exploration (www.thundelarra.com), is situated about 0.5 km southeast of the DeGrussa deposits. Thundelarra Limited reported a drill intersection of 17 m at 11.7% Cu and 1.73 g/t Au. This mineralisation appears to be similar to that of DeGrussa and is hosted in dolerite, gabbro and basaltic rocks. The ore minerals include chalcopyrite, pyrite, pyrrhotite, bornite, covellite and magnetite (Pirajno, unpublished data). Some sections almost entirely consist of massive and disseminated granular magnetite, suggesting a transition to massive sulphides (Pirajno, unpublished data). On the other hand, it is also of interest to note that relics of pentlandite and violarite are also present, hinting at the possibility of a Ni-Cu orthomagmatic mineral system, later overprinted by supergene sulphides (Pirajno, unpublished data).

4.3. Petrography

In this study a number of drill holes were examined, totalling 1721 m and 60 core samples collected for petrographic analysis. The core samples were cut for thin- and polished-thin sections and studied with a conventional polarising microscope. Selected and simplified core logs are shown in Fig. 8A and B and an overview of the main lithologies and sulphide mineralisation is discussed below. Typically, lenses of massive sulphides, zones of brecciated sulphide and stringer zones with disseminated sulphides are hosted in a sequence of dolerite, gabbro and immature siliciclastics.

4.3.1. Conductor 1 orebody

Conductor 1 ore zone has on the hanging wall side fine- to coarse-grained immature siltstone, lithic sandstone and dark-green volcaniclastics. These rocks are characterised by a chlorite-rich matrix, locally overprinted by sericitic patches and cut by calcite veinlets. On the footwall is a gabbroic rock, which mostly consists of plagioclase, orthopyroxene, tremolite, hornblende and disseminated titanite, in places altered to leucoxene. The gabbro is locally brecciated and veined and/or altered to chlorite, epidote and in the deeper sections, near the contact with massive sulphides, it becomes texturally complex and pervasively altered. The alteration assemblage is dominated by quartz, tremolite-actinolite and epidote. The contact with the massive sulphides is marked by intense silicification and mylonitisation (probably a fault zone). The massive ore comprises pyrite, chalcopyrite, magnetite and minor sphalerite, associated with carbonate, white mica and stilpnomelane gangue (alteration) minerals. Dynamically, crystal-plastic (undulose extinction) carbonate grains and patches or fragments, are overprinted by sulphide streaks. Stilpnomelane occurs as acicular crystals in microfractures or forms patches and aggregates associated or included in carbonate. A dominant pyrite-chalcopyrite assemblage forms a coarse-grained complex aggregate, with chalcopyrite generally occurring interstitially in pyrite, possibly post-dating it, whereas in other instance the pyrite-chalcopyrite assemblage fills fractures in sphalerite. The zone of massive sulphides is underlain by a stringer (feeder) zone, which consists of a fine intergrowth of pyrite and chalcopyrite, minor sphalerite and chalco-pyrrhotite (solid solution of $CuFeS_2$ and FeS) associated with fragments of carbonate material, brecciated and overprinted by sulphides. The pyrite-chalcopyrite aggregate is in places cut by chalcopyrite ± sphalerite ± stilpnomelane sinuous veins. In other instances a fragmented carbonate ± quartz ± stilpnomelane is invaded by two generations of sulphides:pyrite + chalcopyrite and chalcopyrite ± sphalerite.

4.3.2. DeGrussa orebody

The DeGrussa orebody is nearly vertical and lies structurally above Conductor 1 (Fig. 7). It has chloritised lithic sediments and volcaniclastics on the structural hanging wall side and mostly basaltic lavas, doleritic and gabbroic rocks on the structural footwall side. The footwall gabbro and dolerite are pervasively altered to an assemblage consisting of epidote, Mg-rich chlorite, sericite, calcite, titanite (altered to leucoxene), albite and quartz, associated with a network of microfractures. At deeper levels (~360 m) pervasive and complex alteration of medium-grained mafic rock (gabbroic) with alteration minerals including chlorite, titanite, sericite, epidote, associated with fractured feldspar showing myrmeckitic-like (symplectic) intergrowths of quartz and sodic feldspar, replacing the primary feldspar; and overprinted by epidote-Mg-chlorite.

Massive sulphides occur between depths of approximately 100 and 280 m. The hanging wall rocks consist of medium- to coarse-grained clastic. Basaltic lava flows and sub-volcanic dolerite

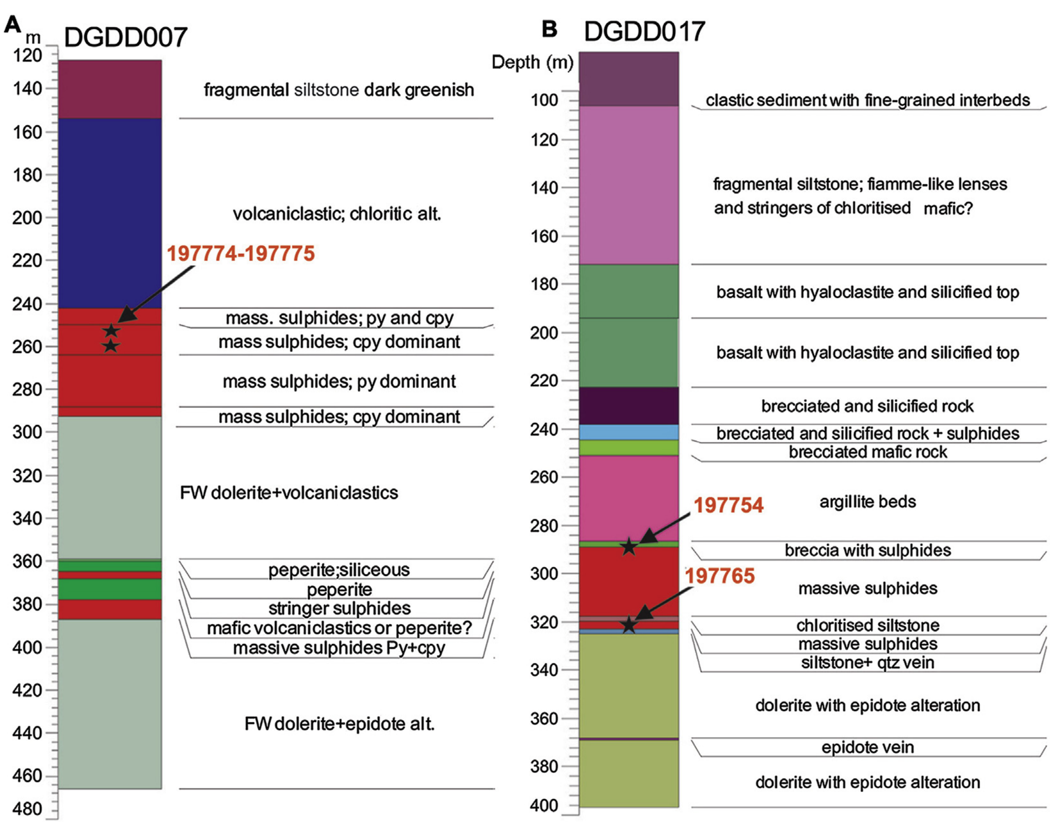

Figure 8. Simplified drill logs (A) Drillhole DGDD0007, (B) DGDD017 with position of samples collected for Re-Os dating.

intrusions, many with peperite margins, and shale beds at the contact with a zone of disseminated sulphides, grade into massive sulphides. The massive sulphides at a depth of 290 m comprise pyrite and chalcopyrite accompanied by minor sphalerite in a talc-carbonate gangue. Three generations of pyrite are identified: (1) massive and intimately associated with chalcopyrite, where chalcopyrite infiltrates boundaries between pyrite blebs; (2) euhedral pyrite (py1); (3) spongy pyrite (py2). Chalcopyrite and pyrite also occur as deformed, streaky patches. Spongy or irregular pyrite grains (py2) are usually associated with or overprinted by chalcopyrite (Fig. 9). All within a matrix of granular quartz gangue cut by calcite and calcite-stilpnomelane veinlets. The calcite veins cut the sulphides. The massive pyrite-chalcopyrite assemblage, overprints grains and bands of magnetite. Sphalerite occurs as small grains included in the dominant pyrite-chalcopyrite assemblage in a gangue of mainly carbonate. Other ore sections exhibit bands of more massive and compact pyrite-chalcopyrite or more comminuted or brecciated pyrite-chalcopyrite-sphalerite-magnetite. A comparatively narrow stringer and brecciated zone, composed of fragmentary magnetite, pyrite and minor chalcopyrite in a gangue of phlogopite, occurs on one part of the massive sulphides zone.

5. Re-Os dating of pyrite from the DeGrussa orebody

Four core samples containing massive primary pyrite were used for Re-Os analyses and age determination. Sample 197754 is from drillhole DGDD017 (core depth of 287 m) and consists of brecciated massive pyrite-chalcopyrite assemblage with minor sphalerite in a gangue of unstrained quartz and calcite. Sample 197765, also from DGDD017 (core depth of 323 m) is massive pyrite with lesser chalcopyrite and magnetite in a gangue of strained calcite. Samples 197774 (251 m) and 197775 (261 m) are from drillhole DGDD007, both consist of massive pyrite and chalcopyrite in approximately equal amounts. The position of the above samples in drill core is shown in Fig. 8A and B.

5.1. Analytical procedures

Re-Os isotope analyses were carried out in the Re-Os lab of the National Research Center of Geoanalysis, Chinese Academy of Geological Sciences. The chemical separation procedure (Du et al., 1994; Qu and Du, 2003; Li et al., 2009, 2010; Qu et al., 2009) is described here briefly:

The enriched ^{190}Os and enriched ^{185}Re were obtained from Oak Ridge National Laboratory. A Carius tube (a thick-walled borosilicate glass ampoule) digestion was used (Zhou et al., 2012). The weighed sample is loaded in a Carius tube through a thin neck long funnel. The mixed ^{190}Os and ^{185}Re spike solutions and 3 mL HCl, 5 mL HNO_4 and 1 mL H_2O_2 are loaded while the bottom part of the tube is frozen at −50 to 80 °C in an ethanol-liquid nitrogen slush; the top is sealed using an oxygen-propane torch. The tube is then placed in a stainless-steel jacket and heated for 24 h at 230 °C. Upon cooling, keep the bottom part of tube frozen, the neck of the tube is broken, and the contents of the tube are poured into a distillation flask and the residue washed out with 40 mL of water.

The Os is separated by the method of direct distillation from carius tube for 50 min and is trapped in 3 mL of water that is used for HRICPMS (ELEMENT2) determination of Os isotope ratio. The residual Re-bearing solution is saved in a 150 mL Teflon beaker for Re separation.

The residual Re-bearing solution is heated to near-dryness twice. 10 mL of 25% NaOH are added to the residue followed by Re extraction with 10 mL of acetone in a 120 mL Teflon separation funnel. Discard the water phase. Wash acetone phase with 2 mL of 25% NaOH. Transfer the acetone phase to 100 mL beaker that contains 2 mL of water. Evaporate to dryness, and picked up in 2% HNO_3 that is used for the ICP-MS determination of Re isotope ratio. Average blanks for the method are ∼3 pg Re and ∼0.5 pg Os. The analytical reliability was tested by analyses of Certified Reference Materials JCBY.

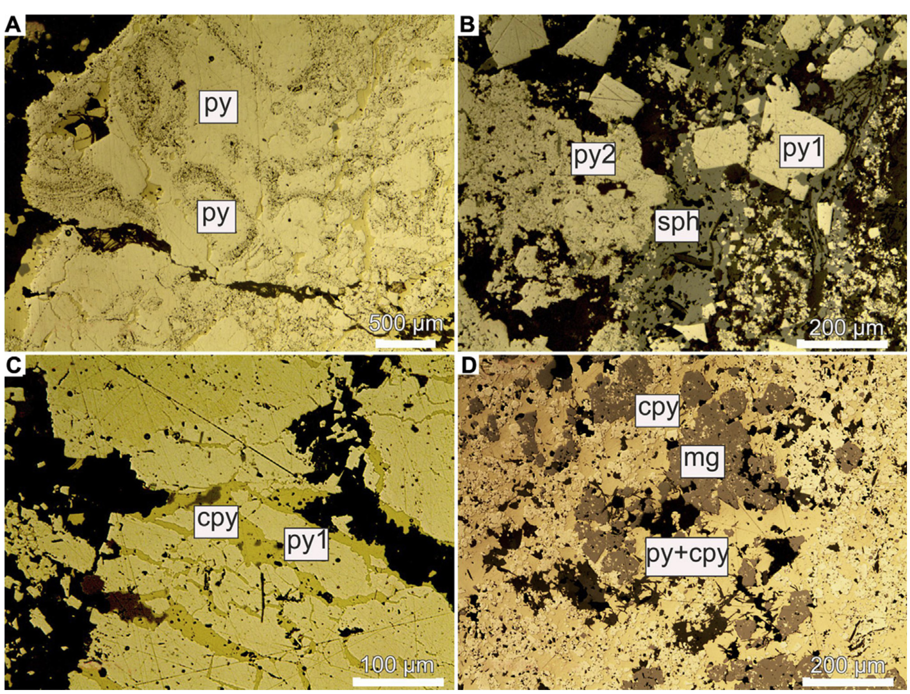

Figure 9. Photomicrographs in reflected light showing some key features of massive sulphides of the DeGrussa orebody (see text for details); py: pyrite, cpy: chalcopyrite, mg: magnetite, sph: sphalerite.

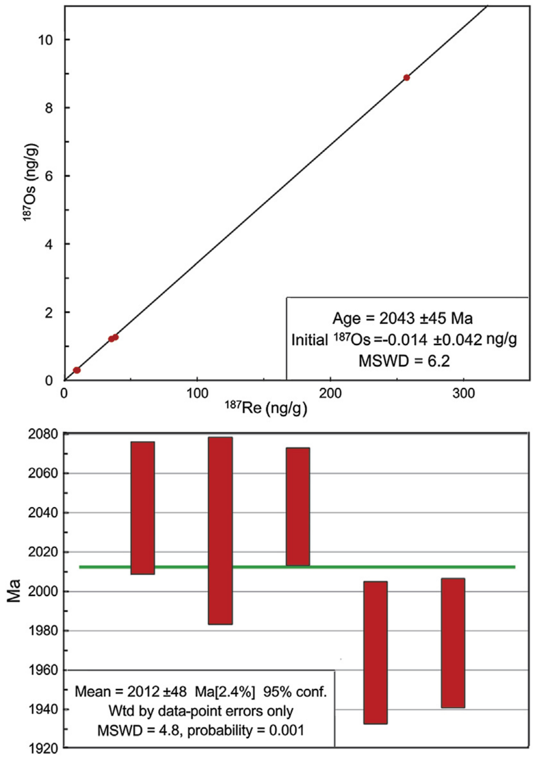

Figure 10. Re-Os dating, (top panel) isochron and (bottom panel) mean age.

5.2. Results

Six measurements of the above samples yield an isochron age of 2032 ± 30 Ma (initial $^{187}Os/^{188}Os = -0.0065 \pm 0.0026$; MSWD = 1.17) and a mean model age of 2012 ± 48 at 95% confidence level (MSWD = 4.8, probability = 0.001). The age plots are shown in Fig. 10 and results of analyses in Table 1. The results pertaining to sample 197765 were considered unreliable and as such excluded from the age calculation.

6. Interpretation of the tectonic setting and geodynamic evolution of the Narracoota and Karalundi Formations: implications for Besshi-type mineral systems

Models for the tectonic setting and geodynamic evolution of the Narracoota and Karalundi Formations were formerly based on the results of field observations (e.g. Adamides, 1995; Pirajno et al., 1998; Pirajno and Occhipinti, 1998; Occhipinti and Myers, 1999). Pirajno (2004b) proposed that accretion of an oceanic plateau due to mantle plume activity were ultimately responsible for the presence of the Narracoota and Karalundi Formations in the Bryah rift-basin. However, this geodynamic model, while accounting for field observations, it did lack geochronological constraints. Recent Re-Os dating of pyrite and molybdenite from the DeGrussa deposit, provided a reliable age constraint for both the origin of the mineralisation and the geodynamic evolution of the Bryah rift-basin. Re-Os dating on molybdenite was performed by Hawke et al. (2014, 2015) yielding ages of 2027 ± 7 Ma and (2011–2013)± 7 Ma (DeGrussa, Conductors 1 and 4), confirms within errors the Re-Os age data (2012 ± 8 Ma) of the pyrite reported in this paper.

Pirajno et al. (2000) and Pirajno and Occhipinti (2000) proposed that the mafic, ultramafic and lesser felsic rocks of the Narracoota Formation are remnants of oceanic crust material accreted onto the rifted margin of the Yilgarn, during the Glenburgh Orogeny, which involved the convergence and collision of the Gascoyne Terrane with the Yilgarn Craton at about 2.0–1.96 Ga (Occhipinti et al., 2004). In this model, a mantle plume impinged at the Yilgarn's northwestern cratonic boundary at approximately 2.0 Ga, causing uplift, rifting and extensive volcanism (Pirajno, 2004b). This uplift and rifting caused the fragmentation of the northwestern margin of the Yilgarn Craton, which split it into two fragments, now shown by the Marymia and Goodin Inliers (Fig. 1). Narrow rift basins developed between these fragments and the margin of the Yilgarn Craton, in which the immature terrigenous sediments of the Karalundi Formation accumulated. As mentioned above a zircon population with ages of ca. 2.7 and ca. 2.0 Ga (Halilovic et al., 2004), supports its derivation from Yilgarn Craton rocks and perhaps also from rocks of the southern Gascoyne Province (Occhipinti et al., 2004). This would imply that uplift affected both continental margins (Gascoyne and Yilgarn) producing rift basins and high energy sedimentation sourced from both regions. The dichotomy in the nature of the mafic-ultramafic rocks of the Narracoota Formation and the mafic rocks of the Noonyereena Member is a critical factor in the understanding of the geodynamic history of the Bryah Rift-Basin. The basaltic lavas of the Noonyereena Member were erupted in shallow seawater, forming hyaloclastites and volcanic breccias. Seawater sodic metasomatism acted immediately, effectively changing the composition of the lavas, which acquired abundant Na, thereby becoming albite-normative. These rocks compared to the mafic and ultramafic rocks of the Narracoota Formation, show moderate enrichment in silica, Ti, lower Ni/Cr and $(La/Yb)_N$ and $Mg^{\#}$ (Pirajno, 2004b). These chemical differences suggest that a more enriched source provided the basaltic hyaloclastites, possibly due to crustal contamination, or transfer of mantle melts towards thinner lithosphere adjacent to a rifted cratonic margin.

With reference to Fig. 11, we propose a new model as follows: (A) mantle plume upwelling at about 2020 Ma impacted on the Yilgarn northern sector (present day coordinates) of cratonic keel, inducing doming of the crust, followed by incipient rifting, as usually observed in such cases (Pirajno, 2009; Avni et al., 2012). This incipient rifting promoted the eruption of intraplate volcanics, as observed for example in the East African Rift System (Pirajno, 2009 and references therein; Ernst and Bell, 2010; Beccaluva et al., 2011). Thinning of the crust and subcontinental mantle lithosphere resulted in mafic underplating, adiabatic melting and denudation (e.g. Tiley et al., 2004). We interpret the undeformed and well-preserved volcaniclastic units in the Bryah rift-basin south of the Murchison Fault to be the remnants of an intraplate volcano

Table 1
Re-Os analyses.

Mineral	Sample no.	Weight (g)	Re (ng/g)	2σ	Common Os (ng/g)	2σ	^{187}Re (ng/g)	2σ	^{187}Os (ng/g)	2σ	Model age (Ma)	2σ
Pyrite	197754	0.30785	56.67	0.52	0.0228	0.0011	35.62	0.32	1.233	0.014	2042	34
Pyrite	197774	0.40589	14.72	0.13	0.0007	0.0015	9.250	0.083	0.3183	0.0064	2031	48
Pyrite	197775	0.10076	409.2	3.6	0.0014	0.0062	257.2	2.2	8.906	0.077	2043	30
Pyrite	197754	0.80107	61.43	0.88	0.0214	0.0003	38.61	0.55	1.287	0.011	1969	36
Pyrite	197774	0.80175	15.16	0.18	0.0069	0.0001	9.526	0.112	0.3184	0.0028	1974	33

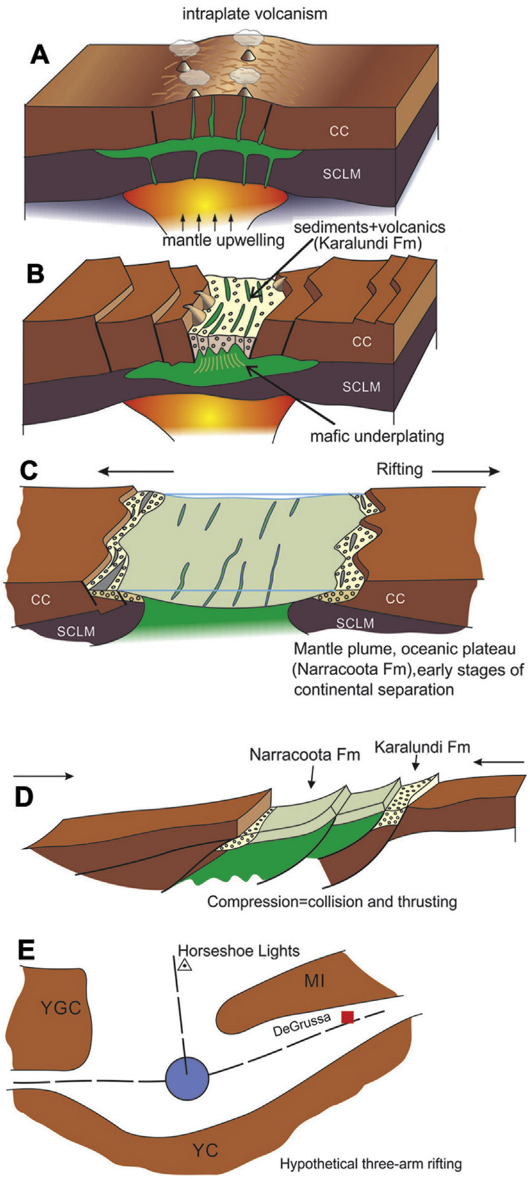

Figure 11. Proposed model for the development of a rift system in the northern margin of the Archaean Yilgarn Craton; (A) intraplate volcanism associated with a crustal uplift caused by upwelling mantle, the undeformed volcaniclastics that occur south of the Murchison Fault are interpreted to belong to this stage; (B) a rift-basin (triple junction?) begins to develop fostering the emplacement of mafic sills and the eruption of basalts in shallow marine water (Noonyereena Member), while at the same time the nascent rift is infilled with immature clastics and turbiditic sediments (Karalundi Formation); (C) the rift-basin progresses with the opening of a narrow oceanic arm and the emplacement of oceanic mafic and ultramafic rocks, which are now represented by the Narracoota Formation; (D, E) during Capricorn Orogeny tectonism with collision of continental plates and accretion occurred with major thrusts and faults bounding the various tectonic units (the Jenkin Fault is one of these). The last panel (E) shows a purely speculative suggestion for the original existence of a triple junction, with the 3 arms constrained by the northern margin of the Yilgarn Craton (YC), the Marymia Inlier (MI) and the Yarlaweelor Gneiss Complex (YGC); interestingly and food for thought is that the age of the Horseshoe Lights kuroko-style VMS (Pirajno et al., 2000; Pirajno et al., 2004) in the north of the Bryah rift-basin ((1985–2000) ± 35 Ma; Hawke et al., 2014) approximately falls within the same range as DeGrussa.

resulting from this initial crustal rifting process. In the next stage (B), the newly formed rift system begins to diverge allowing inflow of seawater, while at the same time volcanism continued, except that in this setting lavas erupted in shallow water, forming the basaltic hyaloclastites, fed by subvolcanic dolerite sills. This magmatism took place at the same time as the deposition of turbiditic and high-energy sediments from the rift shoulders (Karalundi Formation); the interaction between sills and unconsolidated sediments resulted in widespread peperites and the initiation of hydrothermal convection cells, some of which vented on the seafloor, resulting in the development of various stages of sulphide mineralisation (subseafloor feeders, seafloor chimneys). This is the phase responsible for the formation of the DeGrussa VMS, within a package of sill-sediment complex. After the formation of the VMS, emplacement of mafic sills continued, displacing and cutting through the existing VMS system. In the next stage (C) continuing divergence of the rift, due to progressive mantle plume impingement, led to incipient seafloor spreading and the opening of a sea arm with the emplacement of mafic and ultramafic volcanics, sills and sub-seafloor layered intrusions (i.e. Trillbar Complex). The last stage (D) reflects the tectonic events of the Capricorn Orogeny at ca. 1.7–1.8 Ga, which resulted in compression and collisional regimes, with thrusts and tectonic interleaving of individual units. The Narracoota-Karalundi lithologies were faulted against units of the Yerrida Basin to the east (present day coordinates) along forming the northeast-trending Goodin Fault (Fig. 1), which now separates the two lithotectonic units of Bryah and Yerrida. The Jenkin Fault likely developed and progressed at this stage. Panel E in Fig. 11 shows a speculative model envisaging the development of a rift triple junction at the northern margin of the Yilgarn Craton. The DeGrussa VMS would have formed in a narrow failed rift (see below).

6.1. A Besshi-type VMS deposits

We suggest that the tectonic setting of the Karalundi Formation and Noonyereena Member is similar to that of the present-day Gulf of California (Lonsdale et al., 1980; Lonsdale and Becker, 1985; Peter and Scott, 1988; Goodfellow and Nierenberg, 1999), and as such conducive to the development of Besshi type mineralisation. The DeGrussa and Red Bore massive sulphides mineralisation and perhaps other similar occurrences along strike, probably belongs to this class of mineral systems (Slack, 1993; Goodfellow and Nierenberg, 1999; Franklin et al., 2005).

At least six lithostratigraphic types of VMS deposits are recognised (Franklin et al., 2005; Galley et al., 2007): back-arc mafic, bimodal-mafic, pelitic-mafic, bimodal felsic, felsic siliciclastic and hybrid bimodal-felsic. The pelitic-mafic lithostratigraphy fits the Besshi type VMS deposits, which include the type area in Japan, known as Sambagawa belt (upper Palaeozoic) with more than 100 deposits, the deposits of the lower Proterozoic Outukumpu region in Finland, and others in Canada, USA and Norway (Fox, 1984). The Neoproterozoic massive sulphide deposits of the Matchless Amphibolite Belt in Namibia, are also considered to be Besshi type (Klemd et al., 1989). The world's largest Besshi-type deposit is Windy Craggy (British Columbia) containing an estimated 300 Mt of ore grading 1.38% Cu (Peter and Scott, 1988).

The Guaymas Basin, Gulf of California, is considered a modern example of Besshi-type VMS (Lonsdale et al., 1980; Lonsdale and Becker, 1985). The essential prerequisites of these sediment-volcanic hosted ore systems, is that they form in a narrow rift basins, which are generally covered by terrigenous sediments derived from the nearby continental landmass. The terrigenous sediments are intercalated with coeval and discontinuous lenses of mafic rocks. Importantly, seawater dominated hydrothermal convection cells develop in the semi-consolidated sediment pile above mafic intrusions, discharging on at the seafloor, and depositing chemical sediments or exhalites, such as ferruginous cherts. These exhalites are generally the final and/or distal products of submarine hydrothermal discharge and their presence is considered to be an important vector for associated massive sulphide deposits (Franklin et al., 2005). Indeed in areas of Noonyereena Member rocks to the southwest and at the southern margin of the Bryah Basin and to the north along the southern margin of the Marymia Inlier, outcrops of ferruginous chert and banded chert-iron oxides pods are present, testifying to hydrothermal activity and highlighting the potential for further discoveries.

Fig. 12 shows the Gulf of California (Guaymas Basin) idealised model in which terrigeneous sediments and contemporaneous mafic igneous sills are emplaced, accompanied by hydrothermal circulation related to heat energy released by the sills, both below the seafloor and as localised discharges on the seafloor. This is the environment in which the DeGrussa volcanogenic massive sulphide deposit discussed in this paper is proposed to have formed. The Noonyereena Member mafic rocks were emplaced within a narrow rift contemporaneously with high-energy sediments, shed from the rift's shoulders. In the present case of the VMS deposits along the Jenkin Fault a model depicting two-end member stages (initial contemporaneous sedimentation, mafic intrusions and sulphides precipitation, followed by deformation along the Jenkin thrust fault) is shown in Fig. 13. It is interesting to note that a similar sequence of events and formation of Besshi-type VMS is reported from the Irtysh fault zone in the Rudny-Altai region of central Asia (Lobanov et al., 2014).

Ore systems in sediment-covered spreading centres are the above mentioned Besshi district on Shikoku Island in Japan (Slack, 1993), the Windy Craggy deposit in British Columbia (Peter and Scott, 1988) and the massive sulphide deposits of the Matchless Amphibolite Belt in Namibia. In the North China Craton, Li et al. (2004) recognised and reported a sediment-hosted black smoker and sulphide mound complex at Wutai, in a 2.5 Ga ophiolite complex of the Central Orogenic Belt. The origin of the 1.9 Ga Outukumpu Cu-Co-Zn-Ni-Ag-Au sulphide deposits in Finland, have been re-assessed by Peltonen et al. (2007) and considered to be a re-worked turbidite-hosted ore system, tectonically emplaced onto the margin of the Karelian Craton.

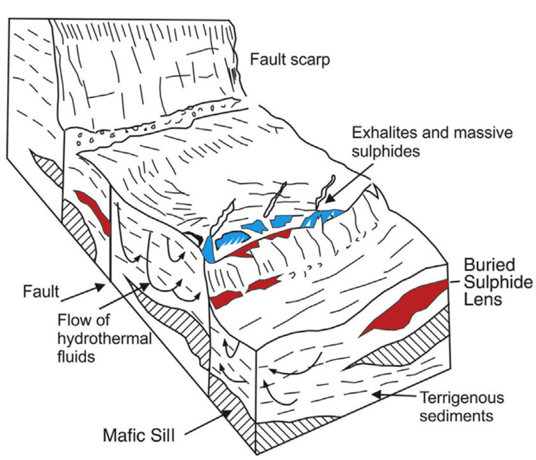

Figure 12. Besshi-type, Guyama Basin (Gulf of California)-style mineral systems; a relatively narrow rift arm bounded by continental areas, characterised by abundant terrigenous immature clastic sediments; high intensity and high T hydrothermal activity, heat sources provided by the cooling dykes and subvolcanic mafic sills, which are emplaced into wet and unconsolidated sediments (hence the peperitic margins that occur between subvolcanic sills and sediments). Metallic oxides, silicates and sulphates occur as encrustations mounds on the seafloor or along fault scarps; disseminated and massive sulphides occur within the sedimentary column and constitute the Besshi-type Cu-Zn deposits. This model is after Pirajno (2009) and is based on and modified from Lonsdale et al. (1980).

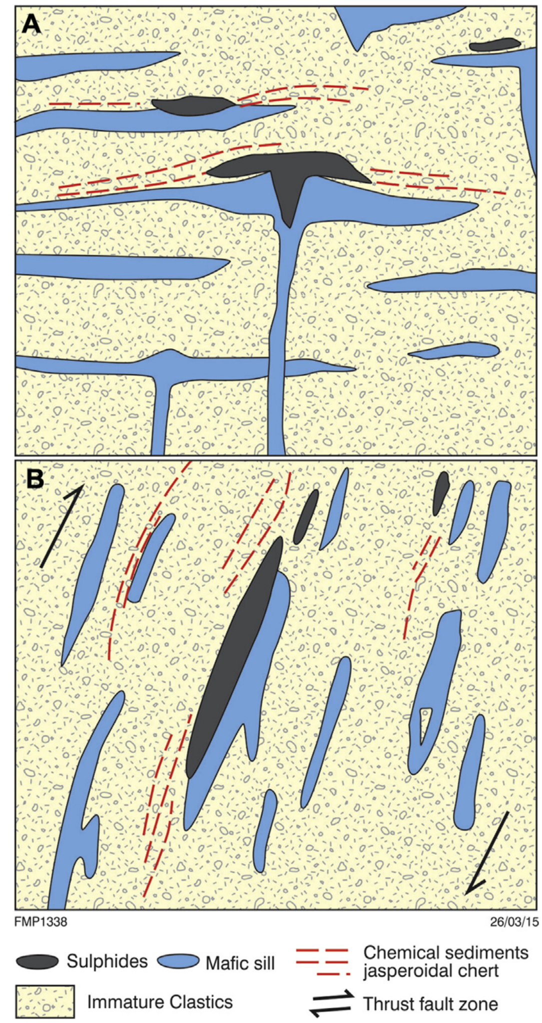

Figure 13. A two end-member stages model (A) pelitic-mafic Besshi-type lithostratigraphic setting (modified after Galley et al., 2007) showing contemporaneous sedimentation and mafic rocks emplacement with localised development of massive sulphides accompanied by deposition of jaspilitic chemical sediments, followed by (B) intense deformation along a thrust fault zone, in our case the Jenkin fault, in which the mafic rocks and sulphides lenses are almost vertical in present-day situation. Figure is not to scale.

7. Conclusions

Massive and disseminated base metal sulphide deposits spatially coincident with a palaeo-rift structure now represented by the Jenkin fault on the northeastern margin of the Palaeoproterozoic Bryah Rift-Basin (Capricorn Orogen) have been studied by field observations, petrographic analyses, carried out during regional geological mapping and drill core logging. Re-Os age data from the DeGrussa deposit indicate that the mineralisation was formed at around 2020 Ma. We propose a Besshi-type model for the origin of the primary sulphide deposits of the Jenkin fault. The *primary* label is used because the DeGrussa and Red Bore sulphide deposits have been subjected to later extensive supergene alteration (and enrichment). Re-Os age data confirm the geodynamic evolution and setting. Our model of geodynamic evolution envisages intracontinental igneous activity, the formation and evolution of a rift system splitting the northern margin of the Yilgarn Craton, the rapid accumulation of immature clastic sediments and contemporaneous mafic lavas and sills. The mafic rocks acted as heat engines for the extensive circulation of hydrothermal fluids, resulting in the inception of a range of VMS occurrences at the site of fluid discharge accompanied by widespread distal chemical precipitates forming the banded jaspilites.

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