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Age, origin and significance of nodular sulfides in 2680 Ma carbonaceous black shale of the Eastern Goldfields Superterrane, Yilgarn Craton, Western Australia

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ABSTRACT

Sulfide nodules composed of pyrite occur within black shales in the Lucky Bay area of the Bulong Domain, Eastern Goldfields Superterrane, Yilgarn Craton, Western Australia that correlate with the Neoarchean Black Flag Group. Detailed petrography reveals a variety of shapes and textures, from spherical to ovoid and zoned to uniform. Some nodules have recrystallized, resulting in a later generation of pyrite. All have been affected by post-depositional metamorphism, as evidenced by pressure shadows containing quartz ± mica ± carbonate assemblages. LA-ICP-MS analyses show that these nodules are enriched in a range of trace elements, including Co, Ni, Cu, Ag, Sb, Te, Au, Tl, Pb, and Bi. Gold and Te concentrations range from 0.3 to 1 ppm and 10 to 50 ppm, respectively. The Black Flag Group equivalents stratigraphically and structurally underlie a younger basin east of Lucky Bay that contains turbidites, sandy debris flows and BIF, the latter of which hosts several gold deposits at Randalls, 60 km SE of Kalgoorlie. It is likely that the lateral equivalents of the nodular sulfide-bearing black shale originally occurred stratigraphically beneath what is now the ore horizon at Randalls. Given its anomalous Au and Te content, this lithology is a potential contributor of gold to the BIF-hosted gold deposits of the Randalls Goldfield, as well as other similar gold resources elsewhere in the Eastern Goldfields Superterrane.

1. Introduction

Nodules or concretions composed of base metal sulfides, particularly iron sulfides, are a common feature in fine-grained sediments deposited in marine basins. Nodular sulfides have also been reported from some carbonaceous chondrites, where their mineralogy is quite complex and exotic relative to terrestrial sulfide nodules (Rubin, 1993; Lin and El Goresy, 2002; Weisberg et al., 2006; Lehner et al., 2008). The morphology of sedimentary sulfide nodules is quite diverse, ranging from near spherical to ellipsoid (the latter often due to post-depositional compaction and deformation) and zoned or unzoned internally (Melezhik et al., 1998). Their textures and mineralogy are just as varied and can include finely intergrown marcasite and pyrite; aggregated framboidal pyrite; fine-grained marcasite with septarian cracks infilled by calcite; intergrown galena and chalcopyrite (Jowett et al., 1991); and intergrown pyrite, pyrrhotite, and carbonate (Melezhik et al., 1998).

Nodular sulfides in Archean and early Proterozoic black shale sequences appear to be no less abundant than those in Phanerozoic sequences, but their occurrences are not as well-reported (Melezhik et al., 1998). In the Mesoarchean Witwatersrand Supergroup of South Africa, pyrite nodules have been reported from the Coronation Formation in the West Rand Group below the major gold reefs (Guy et al., 2011). In the Neoarchean Yilgarn Craton of southern Western Australia, sulfide nodule-bearing black shale (the Kapai Slate) occurs in the Kambalda Ni–Cu sulfide district (Bavinton, 1981) and the St. Ives orogenic Au district (Gregory, unpub. data), while at Mount Charlotte (Au), graywackes belonging to the Black Flag Group contain pyrite nodules up to ~1 cm in diameter (Mueller and Muhling, 2013). Further to the north, in the Archean-Proterozoic Pilbara Craton of northern Western Australia, nodular sulfide-bearing horizons have been documented in the Mount McRae Shale and Whaleback Shale of the Brockman Supersequence (Krapež et al., 2003). The latter two sequences are also intimately associated with banded iron formation. Proterozoic examples of black shale sequences containing nodular sulfides occur, for example, in the ~2000 Ma Pilgujärvi (Productive) Formation of NW Russia (Melezhik et al., 1998), the ~2000 Ma Poorman Formation and ~1880 Ma Nahant Formation, northern Black Hills, South Dakota, USA (Steadman, unpub. data), the 1325 Ma Newland Formation, Belt Supergroup, Montana, USA (Strauss and Scheiber, 1990), and in the shale host rocks to the ~600 Ma Sukhoi Log Au deposit (Large et al., 2007).

Fine-grained, carbonaceous, sulfidic black shale such as that reported here from Lucky Bay is often spatially associated with orogenic gold deposits of all ages around the world (e.g., St. Ives,

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Australia; Sukhoi Log, Russia; Bendigo, Australia; Kumtor, Kyrgyzstan; and Muruntau, Uzbekistan). Prevailing models for the formation of these gold reserves typically involve syn- or post-orogenic timing of ore deposition and a deep-seated fluid and metal source (Groves et al., 1998; Goldfarb et al., 2005). Recent work by Large et al. (2007, 2009, 2011) and Thomas et al. (2011) on sulfide paragenesis in four sediment-hosted orogenic gold deposits around the world counters the latter component of the reigning paradigm by presenting evidence to suggest the mineralizing fluids and metals may be relatively locally derived (i.e., sourced from the surrounding sediments, which are fine-grained, often carbonaceous and sulfidic). In the deposits studied by these authors, fine-grained carbonaceous sediments containing pyrite and/or pyrrhotite are common to abundant in and around the ore zone, and in these lithologies a multi-stage history of pyrite growth, dissolution, and re-growth is preserved. At Sukhoi Log, fine-grained bedding-parallel pyrite nodules and clusters of micro-euhedra, with a large, diverse trace element inventory (including Au, Ni, Ag, and As) and a broad range in S isotope values, were interpreted to be early diagenetic, while coarser-grained pyrite with subhedral to euhedral crystal shapes and comparatively minor trace element enrichments (i.e., low Au, As, Ni, and Ag) was interpreted as metamorphic or hydrothermal (Large et al., 2007; Chang et al., 2008). Lead isotope analyses of the various pyrite types showed that the early diagenetic pyrite contained the least radiogenic Pb, which supported the paragenetic classifications (Meffre et al., 2008). A complete history of gold paragenesis in the deposit, from sedimentation to ore-formation, was thus developed using detailed petrography, whole-rock XRF, and LA-ICPMS trace element and Pb isotope analyses on individual pyrite generations. A similar multi-faceted geochemical approach has been applied to this study, elucidating the paragenesis of pyrite nodules contained within the carbonaceous black shale at the Lucky Bay gold prospect, and bolstering the arguments put forth in Large et al. (2009, 2011) concerning the origins of sediment-hosted gold resources, which in this case are associated with BIFs.

2. Geological context

2.1. Regional geology – stratigraphy and geochronology

The Lucky Bay prospect is located approximately 70 km SE of Kalgoorlie (~35 km E of Kambalda) in the Eastern Goldfields Superterrane (Fig. 1A). The Eastern Goldfields Superterrane (EGS) is a Neoarchean granite-greenstone terrain composed of five NNW-trending arc fragments, termed the Kalgoorlie, Gindalbie, Kurnalpi, Burtville, and Yamarna Terranes (Fig. 1B). Each terrane has its own history, complete with intermediate to felsic volcanic rock packages defined by unique volcanic facies, age, and geochemistry (Swager, 1997; Barley et al., 2008). Nevertheless, the development of the individual terranes was at least partially linked in time and space. Squire et al. (2010) highlight the fact that most of the volcano-sedimentary successions comprising the EGS were created during four separate magmatic pulses, at 2940, 2810, and 2760 Ma, and a protracted episode from 2715 to 2655 Ma (all ages approximate). During these periods, the arc fragments-turned-terranes were physically separate, explaining the relatively minor differences now preserved in the rock record. At ca. 2660 Ma they amalgamated, and by ~2645 Ma were sutured to the preexisting proto-continent (Fig. 1B and C).

SHRIMP and LA-ICP-MS measurements of magmatic and detrital zircon from numerous successions in the EGS have played a key role in elucidating the tectonostratigraphic architechture of the Yilgarn Craton (e.g., Krapež et al., 2000, 2008; Dunphy et al., 2003; Kositcin et al., 2008; Krapež and Pickard, 2010; Squire et al., 2010). These and other research papers provide detailed accounts of the construction of the several sequences contained within each terrane; a summary of the successions in the youngest magamatic episode (2715–2655 Ma) is provided here. The rocks produced during this magmatic pulse are the dominant representatives of Neoarchean volcanism and sedimentation in the Kalgoorlie, Gindalbie and Kurnalpi Terranes. Krapež and Pickard (2010) divide the event into two main stages in each of the three Terranes, with slight differences in timing and petrochemistry. The second stage of Episode 4 is best represented by the Kalgoorlie Sequence, a ~6 km-thick pile of predominantly felsic clastic rocks that stratigraphically overlie the Kambalda Sequence in the Kalgoorlie Terrane. The Kalgoorlie Sequence is also called the Black Flag Group, which includes the Spargoville, Black Flag, and White Flag Formations (Fig. 3; Krapež et al., 2000; Swager et al., 1992). These three components of the Black Flag Group/Kalgoorlie Sequence comprise varying amounts of rhyolitic/dacitic lavas, volcaniclastic breccias/sandstones, turbidites, and carbonaceous shale. The maximum depositional age of the Kalgoorlie Sequence is constrained by two ages: 2692 ± 4 Ma and 2686 ± 3 Ma (both 2σ). The first date is a U–Pb zircon age for the Kapai Slate, an interflow sedimentary unit (including sulfidic black mudstone) within the upper Kambalda Sequence (Claoué-Long et al., 1988). The second date, also a U–Pb zircon age, is from a dacite clast within the basal Black Flag Group (Spargoville Formation; Krapež et al., 2000). The minimum depositional age is believed to be 2658 ± 3 Ma (2σ), which was obtained from a felsic intrusion (Mt. Shea porphyry, Kositcin et al., 2008) that cross-cuts the Black Flag Group south of Kalgoorlie (sample SHD-9, Krapež et al., 2000). Squire et al. (2010) placed the minimum depositional age of the Kalgoorlie Sequence at ~2670 Ma, based on the texture, composition, and zircon age of a sample of sandstone they collected from the upper Kalgoorlie Sequence. This sample (LB212 in their paper) came from a very thick package of quartz-rich sandstone at St. Ives containing volcanic quartz and exhibiting a tight distribution of U–Pb ages (2670–2660 Ma). These characteristics are unlike those of the underlying (and older) Kalgoorlie Sequence units, which are more feldspar- and mafic clast-dominant. Squire et al. (2010) therefore maintain that the felsic intrusion dated by Krapež et al. (2000; sample SHD-9) is more likely to be a constraint on the minimum depositional age of the overlying Merougil Group (see Section 6 for more detail on this issue).

2.2. Regional geology – deformational and metamorphic history

Blewett et al. (2010), building upon the previous work of Swager (1997), presented a new framework for understanding the deformational events that occurred in the Eastern Goldfields Superterrane (EGS) during the late Archean. They highlighted five main structural events (D_{1-5}), of which D_1, D_2, D_3, and D_4 are of greatest relevance to this paper. D_1 (‘DE’ in Swager, 1997) was the longest-lived of the five, commencing ~2810 Ma and ending at approximately 2670 Ma. It was an episode of east-northeast extension, primarily responsible for the volcanism and deposition associated with the Kambalda and Kalgoorlie Sequences in the Kalgoorlie Terrane (and correlatives in the Gindalbie and Kurnalpi Terranes) as well as the strong NNW-trending structural fabric of the entire Eastern Goldfields Superterrane. The subsequent D_2 event (ENE-WSW compression; ~2668 Ma) formed a weak fabric and open, upright folds in pre-2670 Ma units across the Superterrane. D_3 (ENE-WNW extension) began at around 2665 Ma in the Kalgoorlie Terrane. This second extension event created the depo-centers for granitic detritus shed off the basement domes, which are now the so-called late-stage basins, the final products of Neoarchean sedimentation in the Eastern Goldfields Superterrane. One of these late basins, the Belches Basin, is host to the Randalls BIF-gold district. The last episode, D_4 (‘D_2'’ in Swager, 1997), is