

# Iron–manganese oxides and glauconite-bearing rocks of the Earraheedy Group: implications for the base metal potential of the Earraheedy Basin

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## Abstract

The Palaeoproterozoic Earraheedy Basin is characterized by an accumulation of clastic and chemical sedimentary rocks, Lake Superior-type granular iron-formations, and carbonates. Facies rich in glauconite are associated with the clastic sedimentary rocks. Shale units of the Karri Karri Member (Chiall Formation) host iron- and manganese-oxide mineralization. This mineralization is present as structurally controlled veins or thin beds also anomalous in copper, lead, cobalt, and barium. The association of glauconite-rich beds and stratiform iron–manganese oxides is typical of continental shelf environments. This association and the tectonic model for the Earraheedy Basin predict that stratabound sulfide deposits may be present as lateral facies-equivalents of glauconite-bearing sandstones and the iron and manganese oxides.

**KEYWORDS:** Earraheedy Basin, glauconite, iron, manganese, stratiform deposits, stratabound deposits, tectonics

## Introduction

The Palaeoproterozoic (c. 1800 Ma) Earraheedy Basin (Bunting, 1986; Pirajno et al., 1999; Jones et al., 2000) is at the eastern end of the Capricorn Orogen, a zone of low- to high-grade metamorphic rocks, granite intrusions, and volcano-sedimentary and sedimentary basins. The Capricorn Orogen developed as result of the collision between the Archaean Pilbara and Yilgarn Cratons between 1830 and 1780 Ma (Tyler and Thorne, 1990; Tyler et al., 1998; Occhipinti et al., 1999a,b).



The Earraheedy Basin contains an approximately 5000 m-thick succession of clastic rocks, carbonate rocks, and iron formation of the Earraheedy Group deposited in a shallow-marine to coastal setting. The stratigraphy of the group is shown in Figure 1 and discussed in Jones et al. (2000). The basal units of the Earraheedy Group are included in the Tooloo Subgroup (Fig. 1), and have a total thickness of about 2500 m. Rock types in this subgroup are sandstone, stromatolitic dolomite (Yelma Formation), granular iron-formation interbedded with shale (Frere Formation), and finely laminated iron-rich

shale and limestone (Windidda Formation). Overlying these basal units are 2700 m of clastic and carbonate rocks of the Minningarra Subgroup, which is subdivided, from oldest to youngest, into the Chiall Formation (quartz sandstone, siltstone, and mudstone), Wongawol Formation (shale, siltstone, and fine-grained sandstone), Kulele Limestone (a platform carbonate succession with stromatolites), and Mulgarra Sandstone (a molasse-type unit, recording the final influx of terrigenous sediments).

On the basis of stratigraphic and sedimentological constraints, the Earraheedy Basin is interpreted as the shelf remnant of a passive continental margin, with the rest of the margin now buried beneath the younger Bangemall and Officer Basins (Pirajno et al., 1999; Jones et al., 2000). Compressive movements, perhaps linked to collision between the West Australian Craton and North Australian Craton at about 1760 Ma (Yapungku Orogeny; Smithies and Bagas, 1997; Tyler et al., 1998), resulted in a zone of deformation along the exposed northern margin of the Earraheedy Basin (Stanley Fold Belt; Pirajno et al., 1999).

The iron–manganese mineralization locally present in rocks of the Windidda and Wongawol Formations are discussed, and the significance of widespread glauconite in the clastic units of the Chiall and Wongawol Formations examined.

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BUNTING (1986)	REVISED STRATIGRAPHY	SUBGROUP	THICKNESS
Mulgarras Sandstone	Mulgarras Sandstone	Minningarra Subgroup	~100 m?
Kulele Limestone	Kulele Limestone		~300 m
Wongawol Formation	Wongawol Formation		~1500 m 
Princess Ranges Quartzite	<div>Chiall Formation</div> <div>Karri Karri Member</div> <div>Windidda Formation</div>		~1000 m
Wandiwarra Formation			
Frere Formation	<div>Frere Formation</div> <div>Windidda Formation</div>	Tooloo Subgroup	~1800 m 
Yelma Formation	<div>Sweetwaters Well Member</div> <div>Yelma Formation</div>		<10 m in southeast to ~1500 m in west

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Figure 1. Revised stratigraphy of the Earahedy Group, showing the position of iron-manganese mineralization (after Jones *et al.*, 2000)

### Iron-manganese mineralization in the Earahedy Group

Iron-manganese mineralization in the Earahedy Basin is present as structurally controlled quartz – iron oxide – manganese oxide veins hosted by steeply dipping shale units of the Karri Karri Member (Chiall Formation), and stratiform iron- and manganese-oxide bands interbedded with sandstone and siltstone of the Wongawol Formation. The distribution of these occurrences is shown in Figure 2.

The quartz – iron oxide – manganese oxide veins have easterly trends, a maximum strike length of about 100 m, and are 2 to 8 m thick. The stratiform iron-manganese oxides are spatially associated with layers of banded siliceous ironstone (jasper) and grey-green chert containing minor amounts of pyrite, chalcopyrite, and sphalerite (Bunting, 1986). The presence of sulfides suggests the establishment of temporary anoxic conditions in a

commonly oxic environment. The nature and composition of the iron and manganese oxides are not known, but it is possible that the main components are hematite and pyrolusite. The host sandstone typically contains detrital white mica, glauconite, and accessory tourmaline and zircon. The host sandstones have adhesion surfaces, symmetrical ripple marks, and small-scale cross-laminations, suggesting deposition in very shallow water and intermittently emergent conditions.

Table 1 presents chemical analyses of samples from the quartz – iron oxide – manganese oxide veins (samples GSWA 132416, 160809, 160810, and 160814) and the stratiform iron-manganese oxides (samples GSWA 160804, 160806, and 152798). These analyses show that, apart from manganese, the oxides are anomalous in copper (up to 1400 ppm), cobalt (up to 620 ppm), barium (up to 7800 ppm), and lead (up to 580 ppm). High barium values suggest the presence of barite,

whereas the high metal abundances (copper, cobalt, and lead) may be due to the fixing of these elements by the manganese oxides.

### Glauconite in the Earahedy Group

Glauconite is a micaceous mineral with the common formula  $(K,Na,Ca)_{1.2-2.0}(Fe^{+3},Al,Fe^{+2},Mg)_4[Si_7AlO_{20}](OH)_{4.n}(H_2O)$ . Glauconite is commonly deposited on shallow-marine continental shelves (at water depths of 50–500 m), and has a spatial association with iron and manganese formations (Kimberley, 1989; Ostwald and Bolton, 1992).

In the Earahedy Group, glauconite is common at several stratigraphic levels and particularly well developed in sandstones of the Chiall and Wongawol Formations. In the sandstone units of these formations, glauconite forms pellets or peloids associated with clastic grains (Fig. 3). Locally, the glauconite pellets are deformed or

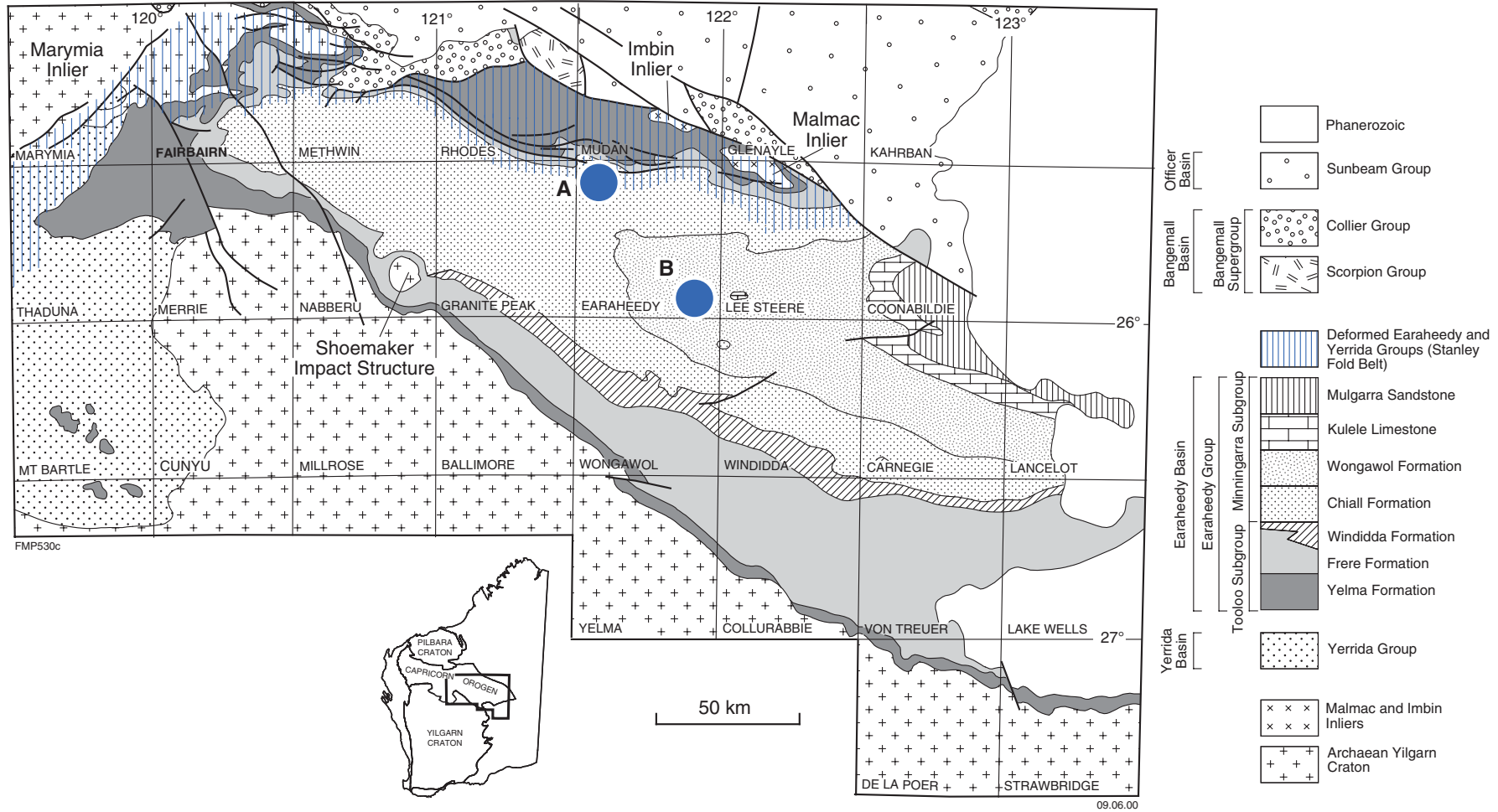


Figure 2 Simplified geological map of the Earraheedy Basin and location of manganese oxide occurrences. A indicates the area of structurally controlled quartz – iron oxide – manganese oxide, and B indicates the area of stratiform iron-manganese oxides. Capitalized names refer to standard 1:100 000 geological maps

Table 1. Analyses of manganeseiferous ironstones from the Earaheedy Basin

Elements	Detection limit	Method	GSWA 132416 <sup>(a)</sup> AMG 350174 <sup>(c)</sup>	GSWA 160809 <sup>(a)</sup> AMG 516677	GSWA 160810 <sup>(a)</sup> AMG 496693	GSWA 160814 <sup>(a)</sup> AMG 498718	GSWA 152798 <sup>(b)</sup> AMG 985306	GSWA 160804 <sup>(b)</sup> AMG 919244	GSWA 160806 <sup>(b)</sup> AMG 858255
Parts per million									
Ag	0.1	A/MS	0.1	0.2	0.3	0.5	0.2	0.3	0.3
As	0.1	A/MS	12	31	10	32	76	9	9
Au (ppb)	1	FA/MS	<1	3	<1	<1	4	x	2
Ba	0.1	A/MS	310	5 200	490	5 400	2 550	4 900	7 800
Bi	0.01	A/MS	0.15	0.14	0.28	0.27	0.03	7.8	10.4
Co	0.1	A/MS	72	265	140	620	3.8	23.5	45
Cr	2	A/OES	16	88	46	10	14	14	20
Cu	1	A/OES	116	1 400	98	98	46	340	320
Mo	0.1	A/MS	0.4	0.8	1.4	4.7	6.6	9.2	10.4
Ni	1	A/OES	15	82	60	145	13	13	23
Pb	2	A/MS	18	26	16	580	34	225	520
Pd (ppb)	1	FA/MS	na	1	x	2	2	1	2
Pt (ppb)	1	FA/MS	na	1	1	5	6	2	5
Sn	0.1	A/MS	0.7	0.8	1.4	1.2	0.3	1	1.2
Th	0.01	A/MS	na	3.4	6.6	5.4	35	6.6	9.8
U	0.1	A/MS	na	6	3.6	2.7	2.15	7.6	8.6
W	0.1	A/MS	0.8	5.6	3.6	0.8	0.5	6.8	4.2
Zn	1	A/OES	155	195	320	760	15	78	114
Mn (wt%)	1	A/OES	7.8	39	19.5	12.5	3	3	9.4
Fe (wt%)	0.01	A/OES	na	4.7	25.5	32	1.75	12.5	14.5

NOTES: (a): From the area of structurally controlled quartz – iron oxide – manganese oxide (see Figure 2)  
 (b): From the area of stratiform iron–manganese oxides (see Figure 2)  
 (c): Localities are specified by the Australian Map Grid (AMG) standard six-figure reference system whereby the first group of three figures (eastings) and the second group (northings) together uniquely define position, on the EARAHEEDY 1:100 000 sheet (Adamides et al., 2000), to within 100 m

A/MS: Multi-acid digest including hydrofluoric, nitric, perchloric, and hydrochloric acids. Analysed by inductively coupled plasma mass spectrometry (ICP-MS)  
 FA/MS: Lead collection fire assay using new pots. Analysed by ICP-MS  
 A/OES: Multi-acid digest including hydrofluoric, nitric, perchloric, and hydrochloric acids. Analysed by inductively coupled plasma optical (atomic) emission spectrometry (ICP-OES)  
 na: Not analysed  
 x: Below detection limit

streaked out, or both (Bunting, 1986), perhaps indicating that they pseudomorphed mud clasts. Petrographically, the glauconite varies from colourless to light green or brown when weathered, or blue-green when fresh. Glauconite is commonly replaced by a mosaic of quartz grains, which are not in crystallographic continuity with the surrounding authigenic silica.

There is an association between glauconite and ferruginous sandstone, with alternations of glauconite-rich and ferruginous layers. Here, the peloids of the glauconite-rich layers are set in a black, fine-grained, probably manganeseiferous material.

### Discussion and implications for base metal mineralization in the Earaheedy Basin

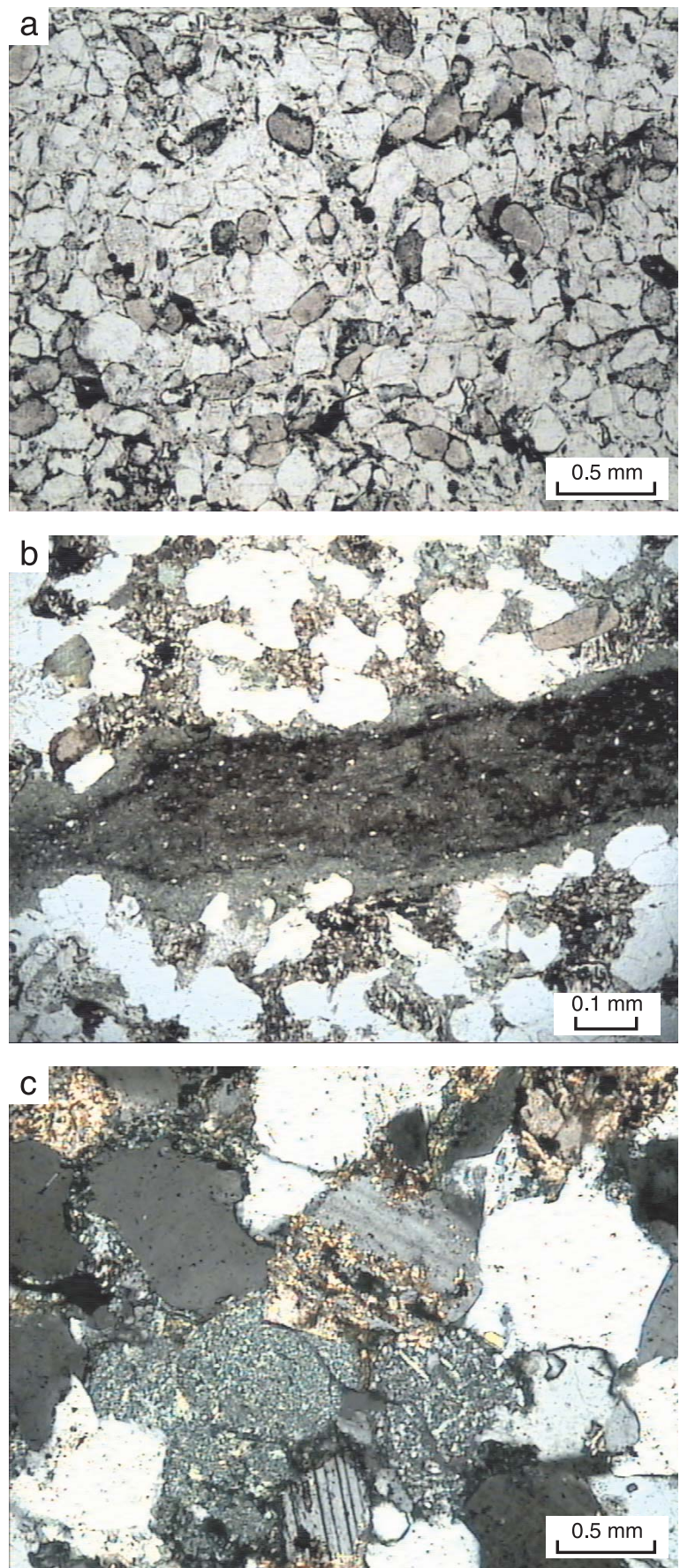
The presence of a thick succession of Lake Superior-type granular iron-

formations in the Earaheedy Basin (Goode et al., 1983), stratiform iron–manganese oxides, and glauconite-bearing sandstones suggests that deposition of these sediments occurred in a continental shelf environment.

Iron and manganese are geochemically similar and, in many instances, precipitated together, but separation can and does occur during precipitation from hydrothermal solutions, depending on Eh–pH environmental conditions. Almost complete separation of these two elements is known from the iron and manganese formation of the Transvaal Basin in South Africa (e.g. Klein and Beukes, 1992). Force and Cannon (1988) suggested that at low Eh, iron solubility is low due to the uptake of iron by sulfur ligands, precipitating sulfides. On the other hand, and under the same conditions, manganese solubility is high because there is no comparable

manganese sulfide (alabandite, MnS, is uncommon in sedimentary rocks; Force and Maynard, 1991). In oxic environments, iron and manganese also tend to precipitate separately, again in response to Eh and pH conditions, with iron oxides predominantly precipitating in deeper water (on the continental slope, at lower Eh for a given pH) and manganese oxides in shallower waters (on the continental shelf, at higher Eh for a given pH; Schissel and Aro, 1992).

Ostwald and Bolton (1992) found a genetic relationship between the glauconite-bearing sandstone and iron–manganese oxides. Glauconite tends to form in deeper offshore water, whereas manganese oxide precipitation occurs along palaeoshorelines. In addition, glauconite enhances the manganese content of the water because it removes iron from the system (Ostwald and Bolton, 1992). In other words, glauconite fixes iron in the clastic sediments, rather



**Figure 3.** Modes of occurrence of glauconite in the Earaheedy Basin: a) clastic quartz, associated with abundant glauconite peloids, many of which are plastically deformed (sample GSWA 152758, crossed polars); b) mudstone clast marginally replaced by glauconite, enclosed in matrix consisting of clastic quartz, feldspar, and glauconite peloids (sample GSWA 160801, parallel polars); c) rounded glauconite peloid partially replaced by euhedral carbonate, which also replaces detrital albite (sample GSWA 160801, crossed polars)

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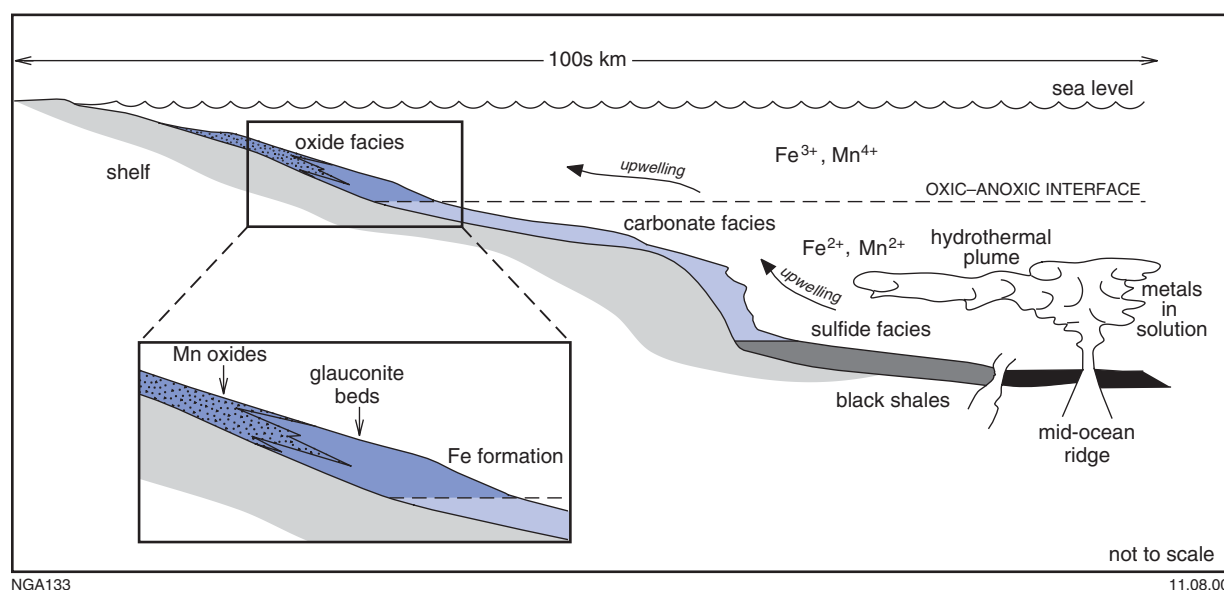


Figure 4 Depositional model of iron and manganese oxides on a continental shelf, and lateral equivalents as carbonate and sulfide facies in deeper settings (modified from Force and Cannon (1988) and Isley (1995))

similar to pyrite fixing iron in black shales. In this way, waters moving along the shelf are enriched in manganese, which is then precipitated as oxide. Anoxic conditions prevail basinward from the iron formation, iron-manganese oxides, and glauconite zones, resulting in deposition of black shales (e.g. Windidda Formation).

The origin of the vast amounts of iron and manganese required to form the observed iron and manganese formations in Proterozoic sedimentary basins is controversial, but a popular view is that subaqueous hot springs are the major source of these metals, as well as of other metals such as copper, cobalt, zinc, lead, gold, and silver (e.g. Isley, 1995). Upwelling currents transport iron and manganese in reduced form ( $\text{Fe}^{2+}$  and  $\text{Mn}^{2+}$ ) from the discharge vents. Precipitation occurs just above the oxic-anoxic interface (Fig. 4), where  $\text{Fe}^{2+}$  and  $\text{Mn}^{2+}$  are oxidized to  $\text{Fe}^{3+}$  and  $\text{Mn}^{4+}$ , with separation constrained by the Eh-pH conditions mentioned above. An important facet of this model (Fig. 4) is that carbonate and sulfide facies (sulfidic shale) are the lateral and deeper water equivalents of iron- and manganese-oxide zones. Black shale-hosted sulfide deposits reported from China and Canada (Coveney et al., 1992)

formed along a transitional shelf zone, between a platform and deeper water setting. In addition, copper, lead, and zinc may exist in deltaic or lagoonal-facies sandstone, vertical or lateral to glauconite-bearing units. A similar situation is recorded from the eastern Atlantic passive continental margin of Africa, between Angola and Gabon, and in Morocco (Caia, 1976), where copper, lead, and zinc deposits are present at several localities in Lower Cretaceous sandstones.

Apart from the iron-manganese mineralization in restricted parts of the Earaheedy Basin, fringing areas of black-shale deposition, the structurally controlled quartz – iron oxide – manganese oxide are hosted by rocks of the Karri Karri Member (Windidda Formation), where they are deformed in the Stanley Fold

Belt. This suggests that tectonism led to the dewatering of the sedimentary succession and the localization of fluids along fractures and faults. If this is correct, then base metal sulfides and gold could be present in areas of the Stanley Fold Belt. This model is supported by auriferous quartz veins in mylonite zones in the Troy Creek area to the west (on the RHODES\* 1:100 000 sheet; Pirajno and Hocking, 2000).

On the basis of the sedimentological character, tectonic setting, presence of iron-manganese oxides and glauconite, we suggest that the Earaheedy Basin is very prospective for stratabound sedimentary rock-hosted base metal sulfide deposits.

\* Capitalized names refer to standard map sheets

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