Magnetic susceptibility of Edmund Basin, Capricorn Orogen, WA

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SUMMARY

Magnetic anomalies appear to be related to base metal prospects in the Mesoproterozoic Edmund Basin of the Western Australian Capricorn Orogen, one of them being the cause of finding the Abra Pb-Cu-Zn deposit. Our results from Edmund and Collier lithostratigraphic units show that magnetic susceptibility of the older dolerites is less than that of the younger, and that weathering appears to decrease the magnetic susceptibility response at outcrops. Sedimentary rocks and Moorarie Supersuite monzogranite have lower magnetic susceptibility than the mafic intrusive rocks. Hydrothermal quartz and diorite related to Moorarie Supersuite have high susceptibility and either of these or both may relate to magnetic highs at locations of outcropping or nearly outcropping basement rocks. Hydrothermal alteration seems linked to higher susceptibilities, but additional sampling from fresh unaltered rock and hydrothermal alteration as well as petrographic studies to define the magnetic accessory minerals in Edmund and Collier Basin lithostratigraphic units are required to understand the link between unit mineralogy and magnetic properties.

Key words: magnetic susceptibility, magnetic petrology, Edmund basin, Capricorn Orogen

INTRODUCTION

Base metal prospects and the Pb-Cu-Zn Abra deposit in the 1620 – 1465 Ma Edmund Basin of the Western Australian Capricorn Orogen appear to be related to magnetic anomalies. Abra is 200 m below the surface, and was found by drilling into bulls-eye magnetic anomaly (Figure 1). These anomalies are likely caused by magnetite replacement of sedimentary strata that was associated with the mineralisation process (Large, 1977). Abra is a blind, stratiform deposit with a funnel-shaped brecciated feeder pipe underneath (Pirajno et al. 2015 and references within). In addition to bulls-eye anomalies in aeromagnetic data, linear magnetic trends follow the trend of bedding within the region. These linear magnetic bodies often correspond to dolerite sills, mapped in the field and are folded into open easterly trending folds. The Edmund Basin contains carbonate and siliciclastic sedimentary rocks of the Edmund Group and is intruded by mafic dolerite sill. The unconformably overlying Collier Group also contains siliclastic sedimentary rocks intruded by dolerite sills. Together the Edmund and Collier groups make up the Bangemall Supergroup.

Magnetic properties of a rock relate to its mineralogical composition and is often referred to as magnetic petrology. Each rock type exhibits a wide range of susceptibility, and though Clark (1997) presents observed and common susceptibility ranges for various rock types, he also states that classic rock names are too broad to be useful for grasping their magnetic properties. This is because susceptibility of most rocks reflects the abundance of accessory minerals, particularly magnetite, which are ignored in petrological classification. Carbonates and clastic sediments generally have very low magnetic susceptibilities, though immature sandstones may contain significant quantities of detrital magnetite (Clark, 1997). Ilmenite series (S-type) granitoids have magnetic susceptibility as low as $*10^{-4}$ SI and magnetite series (I-type) granitoids can contain magnetic susceptibilities going up to $*10^{-1}$ SI and have been known to contain up to 1% accessory magnetite (Clark, 1997). Hornblende-biotite granodiorites are moderately susceptible, whereas muscovite-biotite granodiorites are usually paramagnetic. Ferromagnetic granitoids commonly include accessory titanite, epidote, allanite, pyrite and haemoilmenite or Mn-rich ilmenite (Clark, 1997). Dolerites have moderate to high magnetic susceptibility, but regional metamorphism to greenschist and lower to mid amphibolite grades tends to demagnetise extrusive and hypabyssal micro gabbros, whereas fine magnetic grains within larger silicate crystals in larger gabbro bodies may be preserved (Clark, 1997).

Siliciclastic and carbonate sedimentary rocks form the basin fill of the Edmund and Collier basins and in the field area have been deposited on the basement of Moorarie Supersuite. The Moorarie Supersuite is a group of granites intruded into the southern Gascoyne Complex during the Capricorn Orogeny (Occhipinti and Sheppard, 2001; Occhipinti et al., 2001). Moorarie Supersuite rocks in the study area are mapped as massive, equigranular to sparsely porphyritic biotite-rich monzogranite with minor muscovite in places and they include granodiorite and minor leucogranitic tonalite (Thorne and Cutten, 2011). The basin formations mapped within the Edmund and Collier groups, have been subdivided into six depositional packages of which the five oldest (1-5) are included to this study (Table 1). Modal mineral abundances of sedimentary rocks of Edmund and Collier groups are poorly constrained, and the abundance of accessory minerals, magnetite in particular, is not currently available for the Edmund and Collier basin lithologies. The Narimbunna dolerite sills (1465 Ma) are intruded into the Edmund Group siliciclastic rocks, whereas the Kulkatharra dolerite sills (1070 Ma) intrude both the Edmund and Collier groups (Johnson et al. 2013 and references within). Muhling and Brakel (1985), who did not distinguish between these dolerites, reported that the Narimbunna and Kulkatharra sills contain plagioclase, augite, pigeonite or orthopyroxene, magnetite, subordinate quartz and orthoclase, pyrite and olivine, and their geochemistry is of high-TiO continental tholeiite. The Narimbunna and Kulkatharra dolerite sills were intruded before folding of the Bangemall Supergroup as they are folded themselves and, in some fold cores, have been metamorphosed to chlorite schist (Muhling and Brakel 1985). The Mundine Well dolerite dykes are youngest in the study area (755 Ma) and consist of plagioclase, clino- and

orthopyroxene, olivine, and minor magnetite, pyrite, interstitial quartz-feldspar granophyre, and baddeleyite. These dykes represent the last known igneous event in the region, and are not metamorphosed (Wingate and Giddings, 2000). In the study area the rocks deformed and metamorphosed to prehnite-pumpellyite or greenschist facies during the 1026 to 964 Ma Edmundian Orogeny (Johnson et al., 2013). Other igneous units that contain moderate magnetic susceptibility in the field area could include the older Moorarie Supersuite rocks. For example diorite of the Moorarie Supersuite is intersected in drillcore (CD1) in the region and reportedly consists of plagioclase, clinopyroxene, orthopyroxene, biotite, and hornblende with minor magnetite, ilmenite and apatite (A1962, 1987).
Magnetic susceptibility measurements and sampling has been carried out at outcrops and available drillcores (MJGD2, MJGD27 and CD1 in Figure 1) of the Edmund and Collier basins for 2.5D joint inversions of magnetics and gravity and will be used in geological interpretation of magnetic data in the area. This part of the project aims at determining the magnetic response to base metal mineralisation and alteration within the region, in addition to mapping out large scale structures, and structural complexities that could have acted as mineralising fluid pathways and physical traps. Herein we present observations made pertaining to magnetic susceptibility data measured from the area.

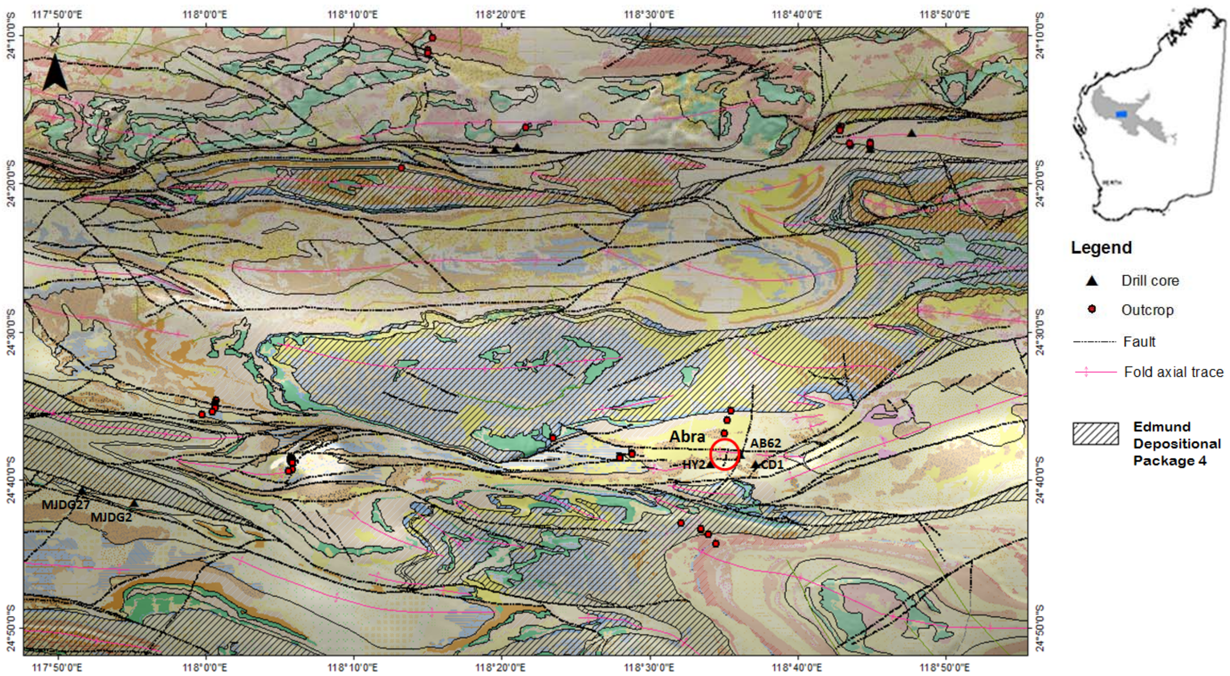

Figure 1. The location of outcrops (red dots) and drillcores (triangles) sampled for magnetic susceptibility. Geological 100k maps are draped over TMI map highlighting magnetic features. Black dashed lines are major faults and the Edmund Basin Depositional Package 4 is covered with inclined hatch to separate the Abra deposit (red circle) hosting the Edmund Depositional Packages 1 and 3 from the Collier Basin.

METHOD AND RESULTS

A Terraplus Magnetic Susceptibility Meter KT-10 was used to record 50 magnetic susceptibility measurements per outcrop at 40 locations covering five out of six depositional packages and most rock types mapped within the lithostratigraphy of the Bangemall Supergroup. Formations that were mapped and sampled as part of this study are marked in the stratigraphic succession of the Edmund and Collier Basin in Table 1. In addition the magnetic susceptibility of the Narimbunna dolerite and drill core intersections logged as 'diorite' from the Geological Survey of Western Australia core library located in Carlisle, Western Australia are included in the study. Magnetic susceptibility was collected from drillcores intersecting Narimbunna dolerite to investigate the influence of weathering by comparing the magnetic susceptibility of fresh drill core samples to those measured from outcrop. In total 2200 magnetic susceptibility measurements were collected from outcrops and 50 from drillcores MJGD2, MJGD27 (Narimbunna dolerite) and CD1 (Moorarie diorite). Collected data was compared to magnetic susceptibility data from two drill cores; AB62 (Hardy, 2013) and HY2 (Murphy, 2011) that are located in the distal part of the Abra deposit. Magnetic susceptibility from AB62 and HY2 was recorded using Terraplus Magnetic Susceptibility Meter KT-9. The magnetic susceptibility boxplots of igneous rocks are presented in Figure 2 and of sedimentary rocks in Figure 3. Figure 4 shows the magnetic susceptibility in Abra deposit interpreted stratigraphy, and the susceptibility data acquired from outcrop siliciclastic sedimentary rocks and from drillcores HY2 and AB62 are presented in Figure 5. In the plots the whiskers represent the minimum and maximum values, line median, black circle arithmetic mean, and top and bottom of the box 25th and 75th percentiles. Numeric values for sample number, minimum, maximum, median, arithmetic mean and geometric mean for each lithology plot are presented in the Table 2.

Sedimentary rocks and the Moorarie Supersuite monzogranite have lower magnetic susceptibility than the mafic intrusive rocks in the area (Figures 2 and 3). Quartz cap (Figure 2) atop the Moorarie Supersuite monzogranite, which was observed in the field to contain sulphides, is more magnetic than the monzogranite underneath as well as sedimentary rocks of the Edmund and Collier groups (Figure 3). Susceptibility of diorite that is linked to the Moorarie Supersuite (A1962, 1987) has as high susceptibility as dolerites of the Collier and Edmund Basin and diorite was concluded to be the reason for magnetic high in the area in the exploration report A1961 (1987). Magnetic susceptibility decreases with increasing age of the dolerites (Narimbunna ~1465 Ma, Kulkatharra ~1070 Ma and Mundine Well Dolerite suite ~755 Ma, Johnson et al. 2013 and references within). The magnetic susceptibility from the Narimbunna dolerite outcrops was compared to the measurements taken from the two drillcores; MJGD2 and MJGD27 that intersect the unit. The magnetic susceptibility was found to be considerably higher when measured from drillcore, compared to the measurements from outcrops (Figure 2). Outcrops of the Bangemall Supergroup rocks are moderate to deeply weathered, which could be the cause of lower recorded magnetic susceptibilities from outcrops of Narimbunna dolerite. Formation of secondary minerals of low magnetic susceptibility from primary minerals with high susceptibility due weathering could cause reduction the overall susceptibility of a rock. Pathways of formation of secondary minerals through weathering have been presented by Anand and Paine (2002, and references within). Weathering of the Narimbunna dolerite paramagnetic orthopyroxene (Clark, 1997) to smectite and kaolinite which have low magnetic susceptibility (Telford et al., 1990), and magnetite to hematite could explain lower susceptibility readings from outcrop in comparison to drillcore. Despite the proposed affect of weathering, the younger dolerites still have higher susceptibility at outcrop than the Narimbunna.

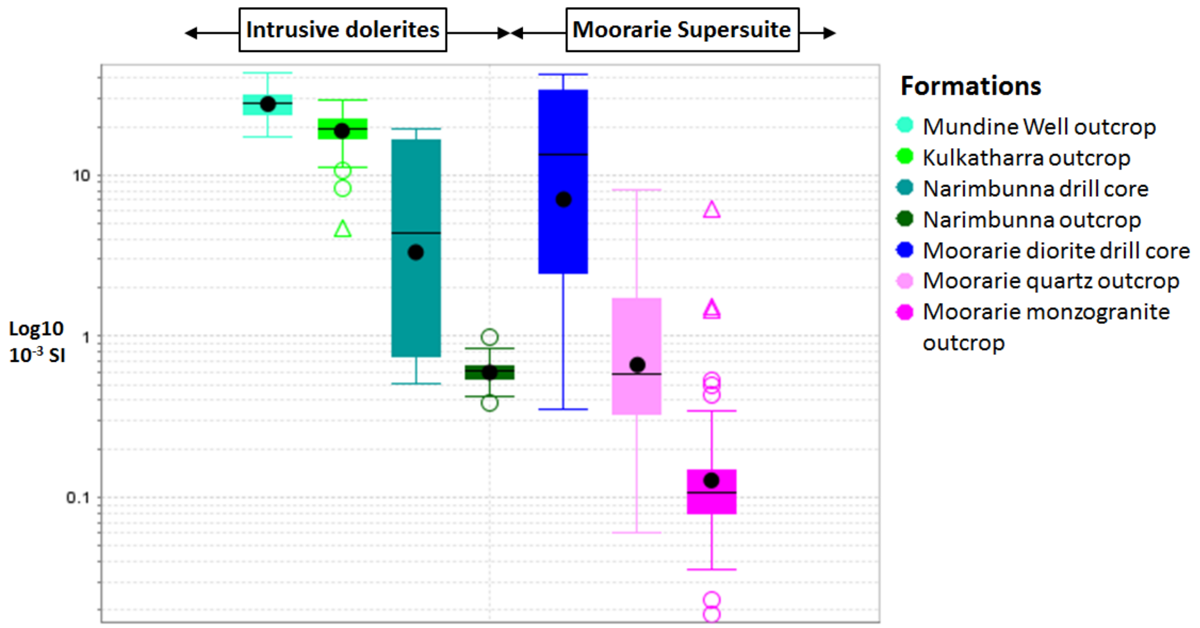

Figure 2. Magnetic susceptibility boxplots for igneous rocks of Edmund and Collier basin. Magnetic susceptibility was measured from outcrop for the Kulkatharra (~1070 Ma), the Mundine Well Dolerite suite (~755 Ma) and drillcore and outcrop for the Narimbunna (~1465 Ma), and drillcore (CD1) for 'porphyritic diorite' that is suspected to be part of the Moorarie Supersuite. The Moorarie Supersuite monzogranite (dark pink) and its overlying hydrothermal quartz cap (light pink) were measured separately on the outcrop. The Narimbunna dolerite is intersected by drill cores MJGD2 and MJGD27 (Figure 1). Whiskers represent the minimum and maximum values, line median, black circle mean, and top and bottom of the box 25th and 75th percentiles.

In Figure 3, sandstone, from different parts of the sedimentary succession contains the highest magnetic susceptibility, whereas dolostones have the lowest. Chert and/or silicified units and dolostones have generally low susceptibility compared to silt and sandstones. The Edmund Depositional Package 4 dolostone has higher susceptibility than dolostones in Edmund 1 and 3, which could be due to magnesite or pyrite in the dolostone. Sandstones in Edmund depositional packages 1 and 3 have the highest susceptibility, which may be explained by presence of detrital magnetite (sensu Clark, 1997). The accessory mineralogy and presence of magnetite, pyrite and magnesite, needs to be verified from thinsections in preparation form hand samples. Magnetic susceptibility of interpreted stratigraphic succession from two distal drill cores, AB62 and HY2, of the Abra deposit is presented in Figure 4. Magnetic susceptibility in the Red Banded Zone (geometric mean 4.8 $*SI^{-3}$) is higher than any of the Edmund Depositional Package 1 and 3 siliciclastic sedimentary rocks and even higher than the magnetic susceptibility measured from drill cores intersecting Narimbunna dolerite (geometric mean 3.3 $*SI^{-3}$). The Kiangi Creek sandstone and the Irregully siltstone intersected by drill core also has higher magnetic susceptibility compared to their counterparts measured at outcrop (Figure 5).

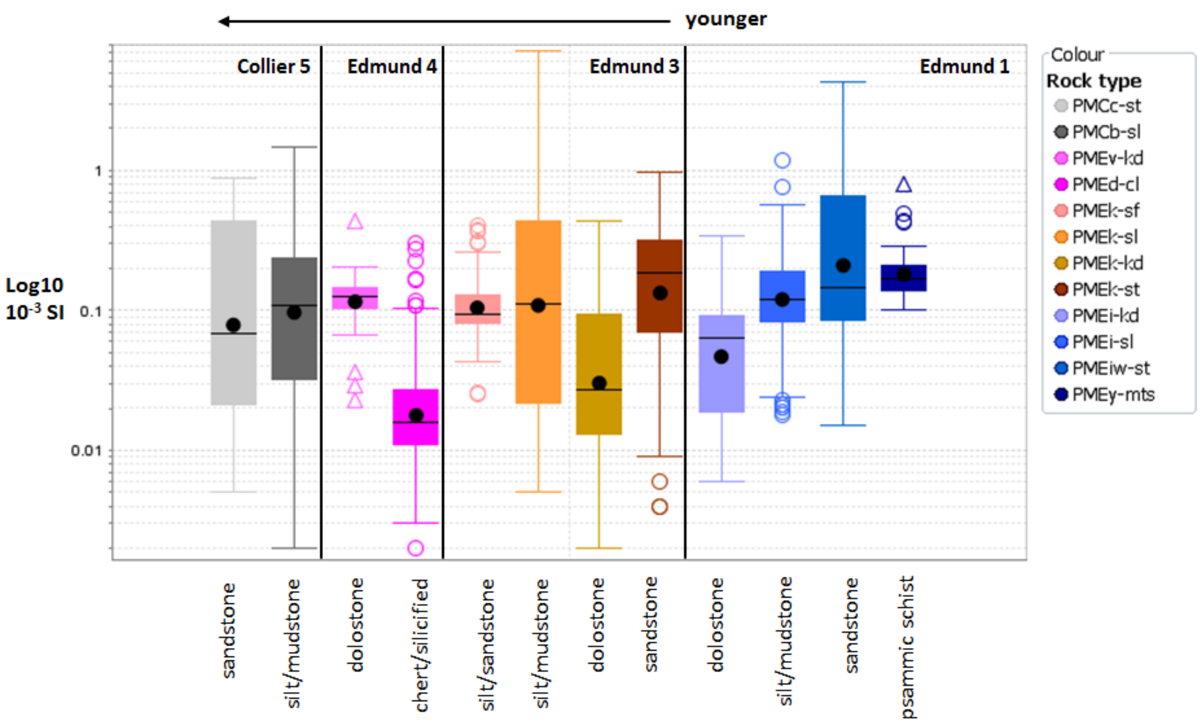

Figure 3. Magnetic susceptibility of 100k sedimentary rocks shown in stratigraphic order, divided by the depositional packages. Rock type of each unit is given in the horizontal axis. Whiskers represent the minimum and maximum values, line median, black circle mean, and top and bottom of the box 25th and 75th percentiles.

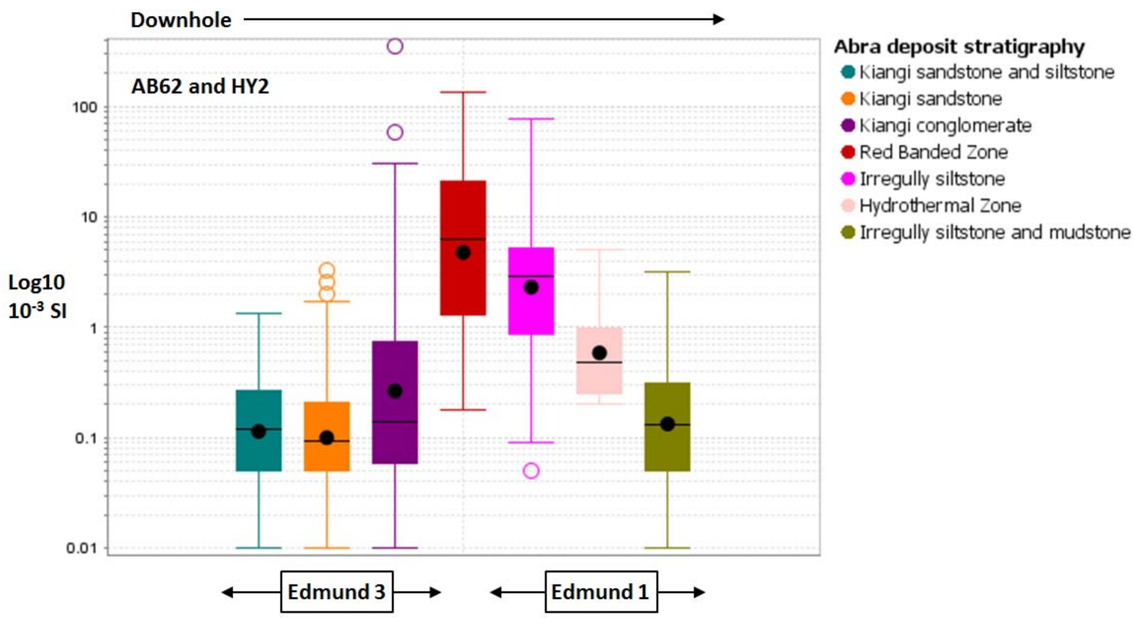

Figure 4. Magnetic susceptibility of logged rock types of the Edmund Depositional Package 1 and 3 from AB62 and HY2 shown in interpreted stratigraphic order of the Abra deposit. Whiskers represent the minimum and maximum values, line median, black circle mean, and top and bottom of the box 25th and 75th percentiles.

Edmund-Collier stratigraphy

GSWA Code	Unaltered siliciclastic rocks	SI-3 Geometric mean
P_-MCc-st	sandstone	0.079
P_-MCb-sl	siltstone-mudstone	0.097
P_-MEv-kd	dolostone/dolomite	0.116
P_-MEd-cl	chert/silicified mudstone	0.018
P_-MEk-sf	siltstone-sandstone	0.104
P_-MEk-sl	siltstone-mudstone	0.105
P_-MEk-kd	dolostone/dolomite	0.030
P_-MEk-ss	sandstone-siltstone	-
P_-MEk-st	**sandstone**	**0.133**
P_-MEk-sp	sandstone-conglomerate	-
P_-MEi-kd	dolostone/dolomite	0.047
P_-MEi-sl	**siltstone-mudstone**	**0.120**
P_-MEiw-st	sandstone	0.210
P_-MEy-mts	psammitic schist	0.181

Abra stratigraphy

Altered siliciclastic rocks	SI-3 Geometric mean
Kiangi sandstone-siltstone	0.243
Kiangi **sandstone**	**0.237**
Kiangi conglomerate	0.085
Red Banded Zone	**4.778**
Irregully **siltstone**	**2.317**
Hydrothermal Zone	0.589
Irregully siltstone-mudstone	0.133

Figure 5. Comparison of magnetic susceptibility geometric means from outcrops of the Edmund and Collier sedimentary rocks and from the intersected lithostratigraphies of the drill cores AB62 and HY2. The mineralised Red Banded Zone has higher magnetic susceptibility than any sedimentary rocks in the Edmund and Collier basins. The Kiangi Creek sandstone and the Irregully siltstone drill core intervals also have higher mean magnetic susceptibility than the corresponding unit outcrops.

CONCLUSIONS

Dolerites are one of the most magnetic units in the Edmund and Collier basins and produce linear magnetic trends in TMI maps that are subparallel to bedding. Weathering seems to influence the magnetic susceptibility recorded from outcrop, and in some cases unweathered equivalent rock has higher magnetic susceptibility. An analysis of the TMI image also shows that the magnetic susceptibility of these units decreases in areas of structural complexity, for example at the trace of the E-W faults. As stated by Clark (1997) the generic modal abundances for rock types even in detailed scale maps were found to outline their magnetic susceptibility only moderately in the study area. Petrographic studies to define the magnetic accessory minerals in Edmund and Collier group units are required to understand the link between unit mineralogy and magnetic properties. Additional magnetic susceptibility measurements from fresh rock are required to determine the effect of weathering to magnetic susceptibility. Susceptibility data measured from hydrothermally altered rocks in drillcore from and outside and in areas of known mineralisation have determined that alteration does influence magnetic properties in the Edmund Basin and may be related to high amplitude magnetic anomalies observed in the airborne magnetic data. These anomalies form circular highs that likely correspond to magnetic mineral replacement of the host sedimentary strata. Whether magnetic mineral replacement is linked or contemporaneous with mineralisation phases is yet to be determined.

ACKNOWLEDGMENTS

We would like to thank the Australian Society of Exploration Geophysics and Society of Economic Geologists for funding field work and the Geological Survey of Western Australia for providing transport, staff and access to drill core. Luke Mortimer, Mike Sloan and Tom Carmichael from MMG are thanked for granting access to the site & supplying accommodation. Lyndon Hardy of Hardy Exploration Services is thanked for sharing his geological insight of the area and Abra deposit.

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Era	Group	Depositional Package 500k	Stratigraphic package description	Formation	GSWA code 100k	Rock type
Meso- Neoproterozoic	***Kulkatharra Dolerite**		Dolerite and gabbro intruded in Collier group			
	Collier	**5**	Shale, siltstone, minor fine-grained sandstone, chert, mudstone, dolostone.	Calyie	*P_-MCc-st	sandstone
					P_-MCc-sl	siltstone-mudstone
				Backdoor	*P_-MCb-sl	siltstone-mudstone
	***Narimbunna Dolerite**		Dolerite and gabbro intruded in Edmund group			
	Edmund	**4**	Siltstone and mudstone; sandstone, dolostone, dolomitic mudstone, chert, and minor conglomerate	Coodardoo	P_-MEc-st	sandstone
				Ullawarra	P_-MEl-sl	siltstone-mudstone
				Devil Creek	*P_-MEv-kd	dolostone/dolomite
					P_-MEv-sl	siltstone-mudstone
				Discovery	*P_-MEd-cl	chert/silicified mudstone
		3	Siltstone and mudstone; sandstone, dolostone, minor conglomerate	Muntharra	n/a	
				Kiangi Creek	*P_-MEk-sf	siltstone-sandstone
					*P_-MEk-sl	siltstone-mudstone
					*P_-MEk-kd	dolostone/dolomite
					P_-MEk-sp	sandstone-conglomerate
					P_-MEk-ss	sandstone-siltstone
					*P_-MEk-st	sandstone
		2	Siltstone and mudstone; sandstone and dolostone; locally sulphidic	Cheyne Springs	n/a	
				Blue Billy		
				Gooragoora		
		1	Stromatolitic and non-stromatolitic dolostone, dolomitic siltstone, sandstone, siltstone, and conglomerate	Irregully	*P_-MEi-kd	dolostone/dolomite
					*P_-MEi-sl	siltstone-mudstone
					P_-MEi-sf	siltstone-sandstone
					*P_-MEiw-st	sandstone
					P_-MEi-ss	sandstone-siltstone
					P_-MEi-st	sandstone
				Yilgatherra	*P_-MEy-mts	psammitic schist
Paleoproterozoic Basement			Gascoyne Province: *Moorarie and Durlacher Supersuite	Metamonzogranite and granodiorite, minor tonalite, syenogranite, gabbro		

Table 1. The stratigraphic succession of the Proterozoic Edmund-Collier basins. Table is compiled after Martin and Thorne (2004), Martin et al. (2008) and Johnson et al. (2013). The units that were measured from outcrop for magnetic susceptibility are marked with asterisk.

Unit Name	**Narimbunna**	**Narimbunna**	**Kulkatharra**	**Mundine Well**	**Moorarie**
Rock type	**Dolerite**	**Dolerite**	**Dolerite**	**Dolerite**	**Monzogranite**
GSWA Code	**P_nr-od**	**P_nr-od**	**P_Wkku-od**	**od**	**P_MO-gmeb**
Source	**outcrop**	**drill core**	**outcrop**	**outcrop**	**outcrop**
n	*102*	*31*	*104*	*51*	*52*
Minimum	0.382	0.508	4.738	17.462	0.019
maximum	0.978	19.285	29.233	42.886	6.159
Median	0.605	7.388	19.384	28.138	0.107
Arithmetic mean	0.617	4.366	19.589	27.932	0.304
Geometric mean	**0.597**	**3.327**	**18.816**	**27.639**	**0.128**

Unit Name	**Kiangi Creek**	**Kiangi Creek**	**Kiangi Creek**	**Kiangi Creek**	**Devil Creek**
Rock type	**dolostone**	**siltstone/sandstone**	**siltstone/mudstone**	**sandstone**	**dolostone**
GSWA Code	**P_MEk-kd**	**P_MEk-sf**	**P_MEk-sl**	**P_MEk-st**	**P_MEv-kd**
Source	**outcrop**	**outcrop**	**outcrop**	**outcrop**	**outcrop**
n	*51*	*51*	*410*	*226*	*53*
Minimum	0.002	0.025	0.005	0.004	0.023
maximum	0.434	0.409	3.351	0.964	0.438
Median	0.060	0.125	0.280	0.214	0.127
Arithmetic mean	0.027	0.095	0.112	0.187	0.125
Geometric mean	**0.030**	**0.104**	**0.105**	**0.133**	**0.116**

Unit Name	**Discovery**	**Irregully**	**Irregully**	**Irregully Woodland**
Rock type	**chert/silicified**	**dolostone**	**siltstone/mudstone**	**sandstone**
GSWA Code	**P_MEd-cl**	**P_MEi-kd**	**P_MEi-sl**	**P_MEiw-st**
Source	**outcrop**	**outcrop**	**outcrop**	**outcrop**
n	*208*	*123*	*195*	*153*
Minimum	0.002	0.006	0.018	0.015
maximum	0.303	0.345	1.171	4.337
Median	0.028	0.065	0.151	0.506
Arithmetic mean	0.016	0.063	0.121	0.144
Geometric mean	**0.018**	**0.047**	**0.120**	**0.210**

Unit Name	**Backdoor**	**Calyie**	**Yilgatherra**	**Moorarie**	**Moorarie**
Rock type	**siltstone/mudstone**	**sandstone**	**psammitic schist**	**Diorite**	**Quartz vein**
GSWA Code	**P_MCb-sl**	**P_MCc-st**	**P_MEy-mst**	**n/a**	**n/a**
Source	**outcrop**	**outcrop**	**outcrop**	**drill core**	**outcrop**
n	*88*	*101*	*53*	*19*	*41*
Minimum	0.002	0.005	0.102	0.353	0.061
maximum	1.483	0.881	0.794	42.556	8.082
Median	0.197	0.205	0.200	16.044	1.229
Arithmetic mean	0.110	0.068	0.167	13.346	0.581
Geometric mean	**0.097**	**0.079**	**0.181**	**7.079**	**0.180**

Table 2. Numeric values of plotted magnetic susceptibilities (SI $*10^{-3}$) in the stratigraphic succession of the Proterozoic Edmund-Collier basins.