A REVIEW

of

RECENT MANGANESE EXPLORATION

in the

BORROLOOLA AREA, ARNHEM LAND, N.T.

Barrie Bolton Consulting

for

Polaris Metals Pty Ltd

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EXECUTIVE SUMMARY

This report reviews recent exploration activities in search of economic manganese deposits in the Borroloola area of Arnhem Land in the Northern Territory. It also presents a guide to manganese exploration in this area based on the world-class manganese deposits mined on Groote Eylandt and recommendations for future work.

The main findings of this review are:

- Rosie Creek South (and the SW Reconnaissance area) prospect, the site receiving the most attention in the recent drilling campaign, contains a small, low-grade manganese deposit that is currently uneconomic. While further drilling is likely to increase the tonnage available there is no evidence this will significantly increase grade and therefore its economic potential;
- Of the 2 remaining drill sites designed to test Cretaceous manganese targets (the other 3 target areas involved Proterozoic rocks), little information is given as to the nature of the host sequence, its age and palaeogeographic setting. While the potential for these areas to host economic deposits of manganese appears low a final assessment will require further work;
- All of the Cretaceous prospect examined are poorly constrained in terms of palaeogeography, age, lithofacies, depositional environment and post-depositional weathering history. These key considerations are presented in a series of exploration guides based on the Groote Eylandt model.

Recommendations for future work include:

- Initiation of palaeogeographic investigations aimed at identifying locations similar to those found on Groote Eylandt;
- Acquisition of samples from across all tenements to better constrain sediment age, nature and depositional setting;
- Review existing geophysical data and acquisition of regional gravity and seismic reflection datasets to better understand palaeogeographic setting, and;
- Conduct widely spaced stratigraphic drilling to confirm geophysical modeling and test for the presence of manganese mineralisation.

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1. INTRODUCTION

At the request of Mr. Jonathan Lea (Technical Services Manager) of Polaris Metals Pty Ltd, Barrie Bolton Consulting Pty Ltd (“BBC”) was commissioned to prepare a Technical Report with respect to recent exploration for manganese in the Borroloola area of Arnhem Land, Northern Territory. The purpose of this report is review existing information on the manganese deposits of the area, to provide a preliminary evaluation of the potential of the area to host an economic manganese (Mn) resource, and to recommend a future work plan.

1.1 Scope of Report

Polaris commissioned BBC to complete a technical review of the prospectivity of the Borroloola area, based on recent exploration, and to provide recommendations for future work.

1.2 Sources of Information

In preparing this report, BBC reviewed unpublished material supplied by Alastair Barker of sister company, MRL, geological and geographical maps, and other public and private information as listed in Section 9 of this report. BBC also participated in discussions with Polaris’s Mr. Jonathan Lea, and MRL’s Mr. Alastair Barker.

1.3 Disclaimer

The opinions expressed in this report have been based on the information supplied to Barrie Bolton Consulting Pty Ltd (“BBC”) by Polaris Metals Pty Ltd (“Polaris”), and related companies. The opinions in this report are provided in response to a specific request from Polaris to do so. BBC has exercised all due care in reviewing the supplied information. BBC does not accept responsibility for any errors or omissions in the supplied information and does not accept any consequential liability arising from commercial decisions or actions resulting from them.

2. TENEMENT LOCATIONS AND ACCESS

The tenements of interest are located approximately 650 km southeast of Darwin, the capital of Northern Territory. The approximate centre of the area is located at UTM 576205E, 8282977N (MGA94, zone 53) and generally lies at altitudes of less than 100 m (Fig. 1). The highest elevations in the region are typically around 200-250 m and occur in a series of elongate ridges oriented approximately north-south that characterise the coastal plain. The area is bordered to the northeast by the shallow waters of the Gulf of Carpentaria, to the northwest by the Roper River, and the southeast, the McArthur River.

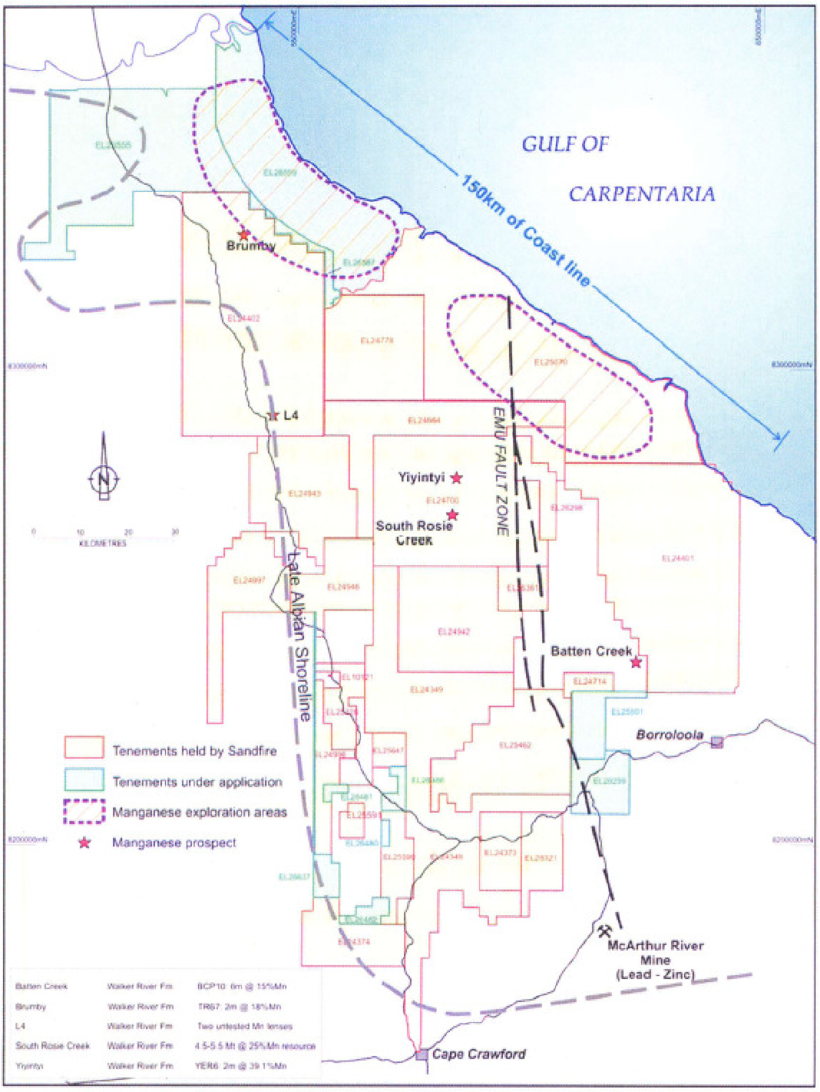

Figure 1. Map showing the location of the Borroloola tenements in Northern Territory. The map also shows the location of the main manganese prospects and approximate position of the Late Albian shoreline.

Access to the Borroloola prospects from Darwin is via a well maintained sealed road from Darwin to the partly sealed Roper River or Carpentaria Highways, south of Katherine, and then via the unsealed Nathan River or Ryan's Bend roads (Fig. 2). Locally, access to prospects is on tracks largely under the management of Lorella Springs Station.

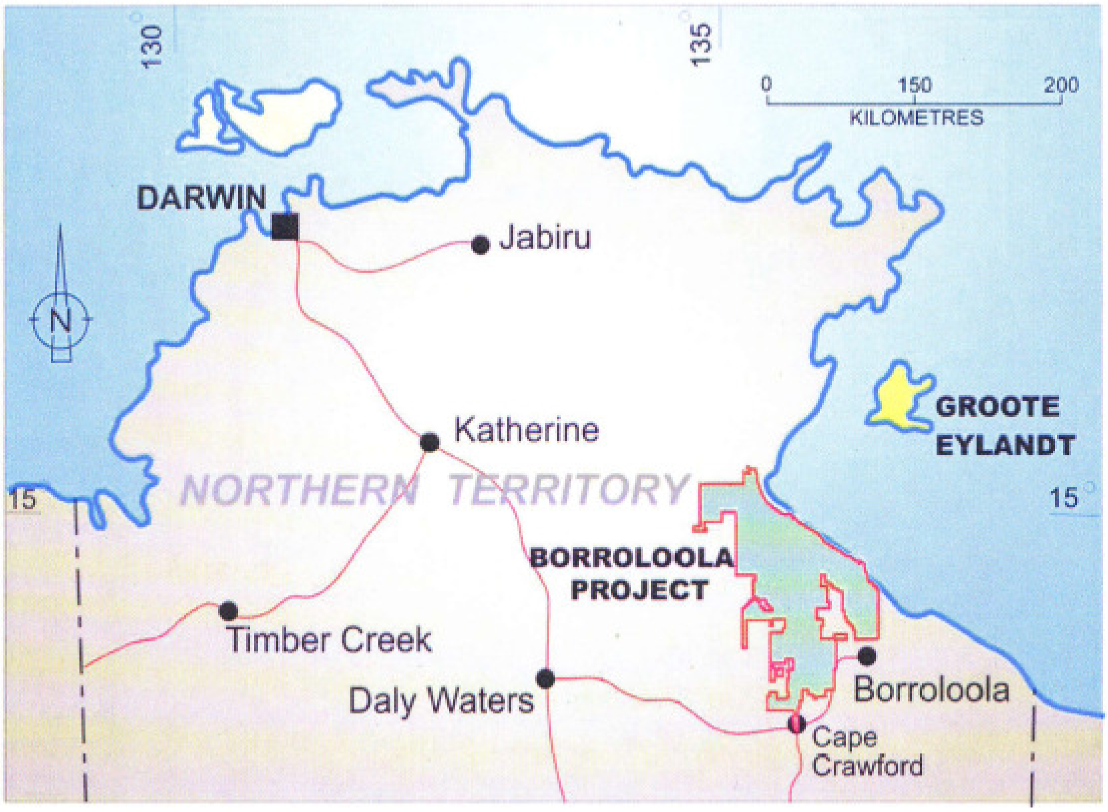

Figure 2. Map showing location and main access roads of the Borroloola area in Northern Territory. Also shown is the location of Groote Eylandt.

3. PREVIOUS EXPLORATION

3.1 Historical Exploration

A comprehensive account of the previous work conducted in the area of interest is provided in Hawke (2009). Other useful summaries of previous work at given by Ferenczi (2001) and Barker (2010). Only a brief summary of the results of this early exploration is given here. This report focuses on the most recent work conducted by Sandfire Resources.

Prompted by the discovery of the world-class Groote Eylandt deposit only 130 km or so northeast of the Borroloola project tenements, most explorers have adopted an exploration model largely based on the style of mineralisation and geological setting exemplified by this mid-Cretaceous deposit. This effort culminated in the discovery in 1994 by BHP of a 4.5 to 5.5 Mt @ 25% Mn (after desliming) deposit at South Rosie Creek (Fig. 1). Other notable Mn intercepts resulting from this effort and based on this model include 6m @ 15%Mn at Battern Creek (on ground presently held by Brumby Resources), 2m @ 39.1%Mn at Yiyinti, 2m @ 18%Mn at Brumby and two untested Mn lenses identified at L4; the last three all falling within current Sandfire tenements (Berents, 1994; Ferenczi, 2001; Hawkes, 2009; Barker, 2010; (Fig. 1).

3.2 Sandfire Exploration

More recently, Sandfire Resources conducted exploration activities aimed at the discovery of an economic manganese resource within their tenement holdings across eastern and southeastern Arnhem Land (Fig. 1). This work included acquisition of airborne VTEM data over the Rosie Creek South and SW Reconnaissance area (July 2008) and, largely based on EM anomalies identified from this survey and earlier data (flown on a 1km line spacing in June/July 1992), the drilling in 2008, of 435 RAB and air core (AC) holes (for a total of 9,773m) to test for economic Mn mineralisation.

In September 2009 Mineral Resources Limited entered into a joint venture with Sandfire Resources for the rights to explore and mine manganese on these tenements. Barker (2010a, b) reviewed previous work done by BHP and Sandfire at the Rosie Creek South and SW Reconnaissance prospects and concluded that the calculated resource was uneconomic and that a technical review of the results to date was required before any further exploration is initiated.

4. REVIEW OF SANDFIRE EXPLORATION PROGRAM

As noted above, Sandfire Resources drilled 435 RAB and air core (AC) holes in 2008 (for a total of 9,773m) on six manganese prospects located within their tenement holdings across eastern and southeastern Arnhem Land (Fig. 1). These drill holes were sited on airborne EM targets broadly similar in character to those associated with high-grade manganese mineralisation on Groote Eylandt.

4.1 Rosie Creek South and SW Reconnaissance Area

Sandfire drilled 386 holes at Rosie Creek South and the SW Reconnaissance prospects for a total of 7,704m. This program was based on the presence of a known Mn deposit (previously drilled by BHP in 1994), the presence of an EM anomaly and close proximity to outcropping basement.

As noted above, BHP estimated a resource at Rosie Creek South of 4.5 to 5.5 Mt @ 25%Mn (Berents, 1994). Hawke (2009) and Barker (2010), using information from the more recent Sandfire drilling, arrive at similar estimates of tonnage and grade. I have reviewed these data and agree with their findings and that based on these estimates, the known manganese resource at Rosie Creek is not economic at the present time.

At Rosie Creek South and the adjacent SW Reconnaissance area, manganese mineralisation occurs mainly in claystone and minor conglomerate at the base of the Cretaceous Walker River Formation at the unconformity with underlying Neoproterozoic Yiyinti Sandstone (Hawke, 2009). The mineralized bed is typically around 2-3m thick and laterally continuous for at least 2km and possibly as much as 5km, in a NNE-SSW direction, adjacent to and approximately parallel to the outcropping Proterozoic sandstones of the North Tawallan Range lying immediately to the east. The mineralisation is of two main types; the first is described as Quaternary in age and comprised of lateritised, reworked and/or transported manganese pisolite; the second type is interpreted to be of Cretaceous age and occurs mainly as submetallic to metallic manganese in banded layers at the base of palaeochannels (Hawke, 2009; Barker, 2010b). Hawke (2009; p. 26) also describes manganese pisolites in thin 'horizons interbedded with clays at the base of Cretaceous channels which are aligned approximately N-S. Previously, Berents (1994) has reported the absence of manganese pisolite and oolite at Rose Creek South and therefore by comparison, a depositional setting somewhat different from that described for the Groote Eylandt deposit. ***From the descriptions given above it is unclear as to whether accretionary manganese particles similar to those that make up the dominant grain type at Groote Eylandt are present at Rosie Creek South. If any of the pisolitic material from this prospect were available then I recommend petrographic analysis to determine whether it is indeed of primary sedimentary or pedogenic origin. This information has important implications for the potential of the area to host large economic Mn deposits of the Groote Eylandt type.***

The sections drawn for the prospect show an abrupt termination of stratigraphic units, including the manganese-bearing unit, against the Proterozoic basement along the eastern boundary represented by the North Tawallah Ranges. The sections at South Rosie Creek generally show a stratigraphic sequence dipping at low angle towards the east away from a basin margin supposedly off to the west. In contrast, Cretaceous units are often shown, to the east, abruptly terminating against rapidly rising basement in a series of basement highs with steep western margins and more gently sloping western margins (e.g. sections 8266100N & 8266000N). While faults are not mentioned in any of the previous accounts, inferred faults are shown on at least two sections (8269500N & 8269600N), terminating gently eastward dipping Cretaceous strata. So, this does raise the question of whether faults are present in the Cretaceous section and indeed whether post-Cretaceous movement has occurred along these faults that might have implications for basin architecture and the distribution of manganese in the region. ***I recommended that a structural analysis of the region be undertaken to better understand the role of deformation in the distribution and internal geometry of Cretaceous units.***

The sections reproduced in Hawke (2009) also show apparently rapid changes in lithology between sections. Although spaced only 100m apart, the Mn mineralisation in sections 8266000mN and 8266100mN ranges from manganiferous clays and claystone in the south to reworked (transported) manganese pisolite in the north, in what appears to be an identical stratigraphic position immediately above Proterozoic basement. The logs from these sections provide little information on the lithological differences between these two sections. ***It would be useful to re-examine the manganiferous materials present in both sections to confirm the apparent differences in their textural characteristics and origin. A better understanding of the textural characteristics of manganese horizons might provide important clues to their depositional setting.***

Furthermore, the sections show only one hole from the SW Reconnaissance area penetrated Proterozoic basement (BLAC384). For the most part manganiferous clays overlie Cretaceous siltstones and fine sandstones. In many sections, oddly, the Proterozoic basement sandstones are shown interstratified with the Cretaceous sediments (e.g. 8269100mN & 8269000mN). ***Many of these sections may need to be re-interpreted and re-drawn.***

The sections drawn for the Rosie Creek prospect, together with available lithologic descriptions, also fail to convincingly establish the location and configuration of the Cretaceous shoreline or the presence of near shore marine sediments; key components of the Groote Eylandt Mn exploration model. ***Given the role of basement topography in controlling the distribution of mineralisation it is recommended that contouring the basement topography and producing isopach maps of the Cretaceous sediments, might be undertaken to gain a better appreciation of the Cretaceous paleogeography during primary manganese deposition.***

There is little in the existing drill logs and descriptions of the Cretaceous sediments to determine much about the depositional environment of the host sequence or indeed that these sediments are of Cretaceous age! The ores on Groote Eylandt are of late Albian to early Cenomanian age (~95ma); establishing that the target stratigraphy contains sediments of this age is an essential part of applying the Groote Eylandt model. Also, there is no evidence provided that supports a shallow water, nearshore, high energy marine origin for the sediments as is the case at Groote Eylandt. Indeed the predominance of finely disseminated Mn in a clay and claystone host suggests a more distal, low energy setting for deposition. ***I recommended, therefore, that any***

future work on these tenements include a range of sedimentological studies to determining the age of sediments and their depositional environment.

The lack of evidence for widespread secondary enrichment of manganese-rich horizons in the sequence is also of concern. This suggests that the stratigraphic section present at Rosie Creek is either too deeply buried to have been exposed to the major supergene events known to have impacted the manganese sediments at Groote, or if they were, they have not been preserved. ***Petrographic investigation of both the Quaternary reworked or transported Mn deposits and underling Cretaceous manganiferous sediments in this region may provide evidence of supergene processes occurring in the region.***

Airborne EM flown over the Rosie Creek South and SW Reconnaissance prospects (in 1992 and 2008) identified several anomalies that have been drill tested. These anomalies are usually interpreted to identify the presence of conductive manganese mineralisation at shallow depth close to areas of outcropping basement, as is the case on Groote Eylandt (Irvine & Berents, 2000). Based on these data it appears that the main geophysical targets have been satisfactorily tested with the possible exception of the region on either side of Rosie Creek itself; between 8268000mN and 8270000mN and west of 5800000mE. However, as noted by Hawke (2009), it must be stressed that there does not appear to be a convincing relationship between the distribution of Mn as determined by drilling, and the EM anomalies. ***I recommend that a suitably experienced geophysicist reappraise all geophysical data used at this prospect to further evaluate its usefulness in targeting Mn mineralisation in this terrain.***

4.1.1 Exploration Potential – Rosie Creek South & SW Reconnaissance

The work to date at the Rosie Creek South and SW Reconnaissance prospects has provided valuable information on the nature of the resource present and, at least locally, a crude appreciation of Cretaceous paleogeography and depositional regime. Many issues, however, remain obscure. For example, the Sandfire test work provides no new information on the distribution, nature and age of surface outcrop within the prospect area. Nor does it say anything about how the age of the sediments intercepted in drill holes was determined or their depositional environment.

Clearly low grade manganese is present over a large area (in excess of 12km^2) at the Rosie Creek prospect. It also appears likely that extensions to the known manganese mineralisation will occur both north and south of the existing mineralisation delineated at the SW Reconnaissance prospect. While this will increase resource tonnages there is little evidence to suggest that it will result in a significant increase in grade. In particular, the apparent absence of condensed, near-shore, primary oolitic and pisolitic manganese oxide units of late Albian/early Cenomanian age and evidence of post-depositional supergene enrichment (at various ages through the Tertiary), suggests grades are unlikely to greatly exceed those seen in the recent drilling program.

It is my view, therefore, that there is little to be gained from further drill testing at the Rosie Creek South and SW Reconnaissance prospects until new targets have been identified following a regional reappraisal of the entire Borroloola area.

4.2 Tawallah 1

Sandfire drilled 11 AC drill holes at the Tawallah 1 prospect based on the presence of an EM anomaly, a Cretaceous sequence onlapping Proterozoic basement and the presence of anomalous Mn in underlying basement rocks. All holes had collar elevations of 105m or more, well above the RL known to contain anomalous manganese in Cretaceous sediments elsewhere in Arnhem Land and Groote Eylandt (Mn ores at Groote Eylandt range from about 20m below sea level to about 50m above sea level).

Mn was recorded in only three intervals; 1-5m depth in BLCA101; 15-16m depth in BLCA105 and 24-26m in BLCA105. The latter intercept was estimated to contain about 2%Mn in what are mainly logged as sandy sediments. Follow up assay results of samples taken from these drill holes shows Mn content ranging from 0.45 to 1.36%Mn. Hawke (2009) notes 'minor manganese-rich fragments and/or pisolites were intersected, yet these were not economically significant.' Proterozoic quartzite forms local basement to the area.

No further information was provided on the basement topography of the area, the depositional environment and age of the Cretaceous sediments, and the nature of any manganese mineralisation present.

4.2.1 Exploration Potential – Tawallah 1

I find it difficult to assess the potential for Mn at this prospect given the paucity of information provided. The relatively high elevation of this prospect compared to the economic deposits at Groote Eylandt may argue against the areas prospectivity however, the suggestion that pisolitic manganese might be present in a sandy Cretaceous host does suggest some similarity to the Groote Eylandt ore deposit model and might therefore indicate the potential for economic mineralisation in this area.

Based on available information I would recommend no further work is undertaken at this prospect pending the outcome of a regional study to identify high priority targets (see below).

4.3 Tawallah 2

Sandfire drilled 7 RAB holes at the Tawallah 2 prospect on the basis of an EM anomaly and ease of access. No information was provided regarding the stratigraphic or palaeogeographic setting of the prospect.

Hawke (2009) says little about the results of manganese exploration in this area rather focusing on the base metal potential of the underlying Proterozoic basement rocks (although this not actually stated).

Assay results on 55 chip samples collected from drill holes at this location show Mn concentrations ranging from 32 to 5736ppm; concentrations for the most part close to average crustal abundance (~950ppm). Available logs of drill samples from the prospect show suspected visible Mn in only two intervals; 1.0 to 5.5m in BLRB004 and 1.0 to 11.50m in BLRB005. No analyses were apparently conducted on either of these intervals.

No attempt has been made to explain the source of the EM anomaly upon which the decision to drill was partly based.

4.3.1 Exploration Potential – Tawallah 2

It is difficult to assess the potential for economic Mn at this location based on the information provided. On the basis of the reported Mn concentrations in these sediments the potential for the discovery of economic reserves appears very limited.

4.4 Yiyinti Range and Yiyinti Range South

Sandfire drilled 21 AC holes at the Yiyinti Range prospect based on the presence of an EM anomaly and proximity to outcropping Proterozoic basement of the Yiyinti Range. Hawke (2009) also reports that no visible Mn was intercepted and that all MnO assays on 5m composite samples from these holes returned valves <0.5%.

No information on the palaeogeographic setting (other than the Cretaceous sequence apparently onlaps the Proterozoic basement at this location) or the depositional environment of the Cretaceous sediments is given for the location.

The cause of the EM anomaly is assigned to the presence of carbonaceous shales, presumably of Cretaceous age. Hawke (2009) notes the presence of 'massive pyrite, binding grains within clays and sands' in samples collected from drill hole BLAC125 (at depth of 42m).

No work was conducted at the Yiyinti Range South prospect because of access issues, according to Hawke (2009).

4.4.1 Exploration Potential – Yiyinti Range and Yiyinti Range South

Again it is difficult to assess the potential for Mn at this location based on the paucity of information on the site.

4.5 Eastern Creek

Sandfire drilled 7 RAB holes at this location based on the presence of an EM anomaly and previous drilling by Carpentaria Exploration, which intercepted up to 25%Mn in Proterozoic age black shales (Mainoru Fm). The black shales were interpreted to be the source of the EM anomaly.

No significant Mn mineralisation was intercepted with assays generally <0.25%MnO.

No Cretaceous sediments are mentioned for the locality so the target here was purely a Proterozoic basement play.

4.5.1 Exploration Potential – Eastern Creek

There would appear to be little or no potential for the discovery of economic manganese in Cretaceous sediments at this location. There also seems to be little potential for economic Mn mineralisation in the Proterozoic basement.

4.6 MYP004 (L4)

Sandfire drilled a single AC drill hole near the L4 manganese occurrence discovered by Carpentaria Exploration. More specifically, the hole was drilled near a Carpentaria drill hole designated, MYP004, located about 15km south of the L4 occurrence (Hawke, 2009). Drill hole, BLAC110, was drilled to a depth of 97m and intercepted mainly shales of the Proterozoic Mainoru Formation. While not discussed by Hawke (2009), the drill target lies on the flank of a weak EM anomaly. The likely source of the anomaly is not discussed.

Assay results from 20 samples collected from this hole gave MnO values ranging from 0.1 to 5.3%, well below the 25.9%Mn concentrations reported from the earlier drilling campaign (Hawke, 2009).

While manganese has been described from the Cretaceous age Walker River Formation at L4, this does not appear to be the target sequence for the Sandfire drilling program reported by Hawke (2009).

4.6.1 Exploration Potential – MYP004 (L4)

There would appear to be little or no potential for the discovery of economic manganese in Cretaceous sediments at this location. There also seems to be little potential for economic Mn mineralisation in the Proterozoic basement.

5. MANGANESE POTENTIAL

Sandfire have to date tested 6 of 13 Cretaceous targets on its tenements. A 14th target tested for Mn mineralisation was sited over known mineralisation of probable Proterozoic age (L4/MYP004).

The untested target areas include:

- The Ruins
- Kulampiri Creek
- Lorella 1
- Lorella 2
- Jumpup Creek
- Yiyenti Range South
- Four Arches

All of these target areas are located over EM anomalies. Some targets are also located over known areas of Mn mineralisation (Yinyenti Range South; Lorella 1) while other targets were selected, in part, because they are located in Cretaceous units that onlap local Proterozoic basement highs. The so-called Brumby target in the northern part of the area under licence – an area of known Mn mineralisation from earlier BHP exploration – while identified as a target (Table 6.1 in Hawke, 2009), was not discussed further in Hawke (2009).

Test work to date has shown that anomalous Mn is widespread in both Cretaceous sediments of the Walker River Formation and probably, the Mainoru Formation of the underlying Proterozoic basement. While all of these Mn occurrences appear to show a general relationship to EM anomalies, in detail the relationship is not clear. For example, at least four areas of the recently drilled Rosie Creek South prospect with known Mn mineralisation at shallow depth occur over areas showing either weak or no EM anomalism.

It appears from these results that the use of airborne EM alone is insufficient as a guide to targeting economic deposits of manganese in the Borroloola area. In the absence of any direct evidence of Mn mineralisation then it is clear other criteria will need to be developed to locate drill targets.

The Sandfire tenements cover a large area of southeast Arnhem Land that in turn contains a broad expanse of Cretaceous rocks and sediments deposited in a palaeogeographic setting very similar to that host the world-class manganese deposits on Groote Eylandt. As described above, anomalous manganese is widespread and many sites remain untested, but with doubts over the effectiveness of largely targeting drill sites on the basis of airborne EM targets alone, other guides to exploration in this highly prospective terrain need to be developed.

In the sections below the Groote Eylandt manganese deposits are revisited and based on the main findings of this review, guides to exploration in the east Arnhem Land region proposed.

6. REVIEW OF EXPLORATION MODEL

6.1 Introduction

In this section I will review the Groote Eylandt deposit model that forms the basis for the Sandfire Mn exploration program in East Arnhem Land (and indeed most other Mn exploration program in this broad region of the Carpentaria Basin over the last 40 years).

6.2 The Groote Eylandt Model

6.2.1 Introduction

Located approximately 640km southeast of Darwin on the western edge of the Gulf of Carpentaria the sedimentary manganese deposits presently being mined by BHP Billiton (60%) and Anglo American Corporation (40%) constitute one of the world's largest and most profitable mines. In 2009 Groote Eylandt shipped about 2.3Mt of ore for a profit of ~$1.1B, to markets, worldwide. In 2009, the total resource for Groote Eylandt was estimated 169Mt with a product grade of 47%Mn. *Insitu* grade is estimated at about 25%Mn and the stripping ratio is 2.18.

To provide a guide to exploration the Groote Eylandt model is discussed below in terms of geology, deposit form and size, the ore and gangue characteristics, geochemistry and geophysics.

6.2.2 Geology/Stratigraphic Setting

Groote Eylandt lies on the eastern edge of the Proterozoic McArthur Basin, and the basement for Cretaceous rocks on the island consists of Proterozoic feldspathic sandstone or orthoquartzite known as the Dalumbu Sandstone (Figs. 3).

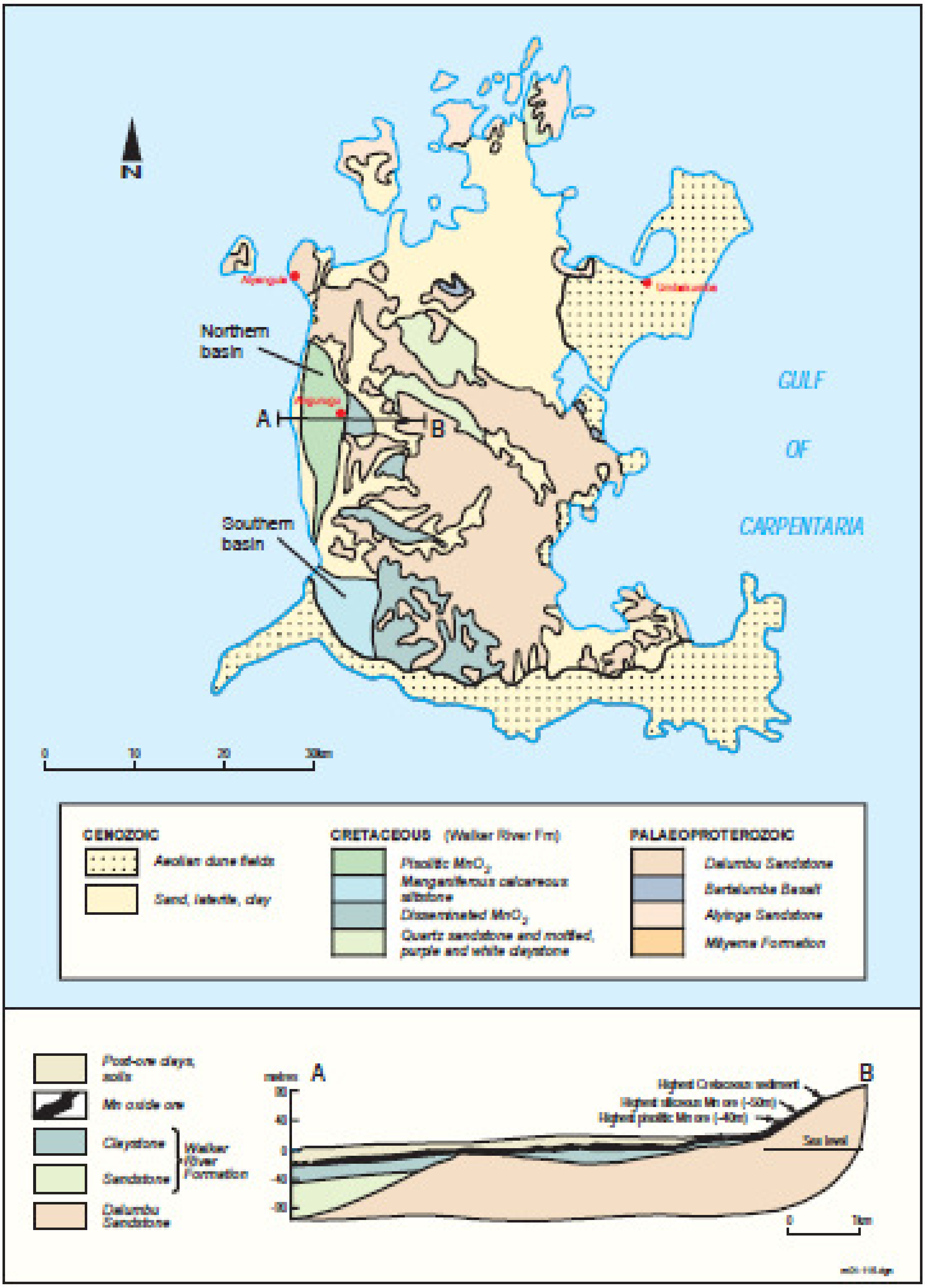

Figure 3. Simplified geology of Groote Eylandt (from Ferenczi, 2001; modified after Bolton et al 1990)

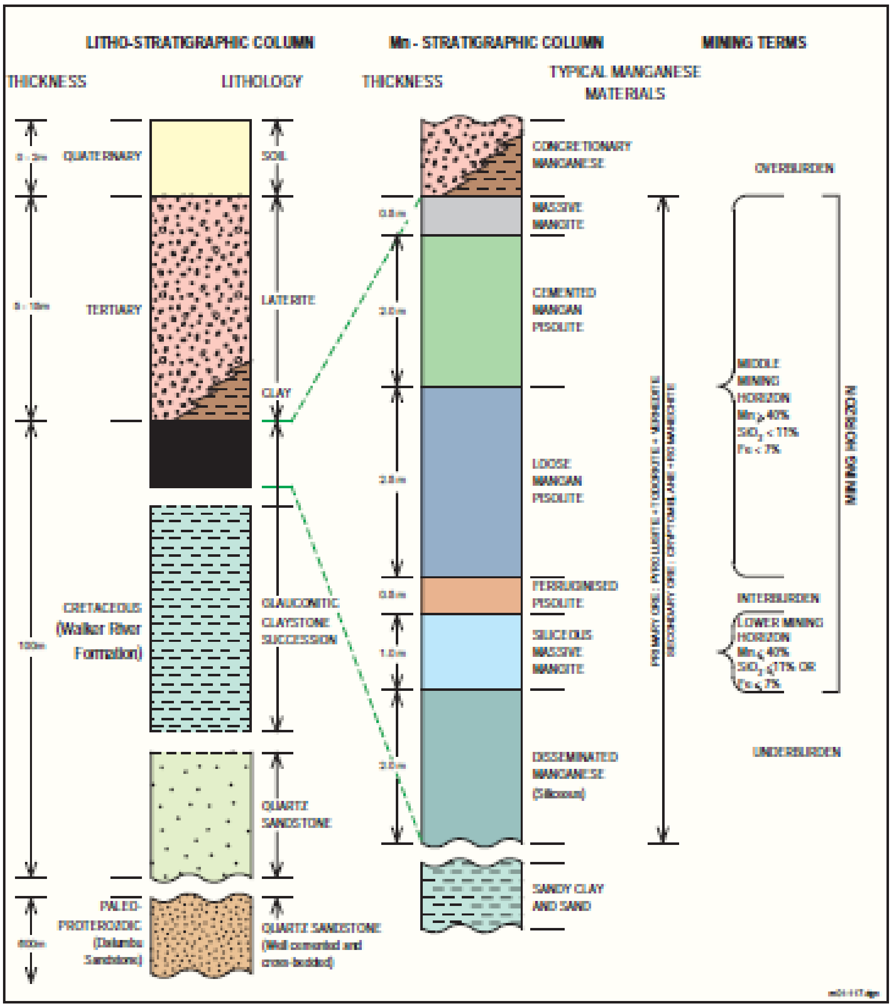

Figure 4. Generalised stratigraphic setting (from Ferenczi, 2001; modified after Bolton et al 1990)

The basement is overlain unconformably by shallow-marine, glauconite sandstones of probable late Aptian to early Albian age (Bolton, 1982; Fig. 4). Overlying these sandstones with a locally disconformable contact, is a thick sequence of claystone, siltstone and minor sandstone of latest Albian to early Cenomanian age. The 'pisolite facies' overlies the clay facies with a regional unconformity and is composed of a thick pisolitic and oolitic manganese oxide/carbonate units (the main ore zone), which are in turn overlain by a series of sandstone, siltstone and claystone units (the overburden). The pisolite facies has a maximum age of late Albian –early Cenomanian based on radiometric dating of glauconite and is capped by a series of Tertiary or Late Cretaceous laterities and soil horizons that range in thickness up to 35m. Overburden averages about 5m in the areas currently being mined.

Cretaceous rocks, known formally as the Walker River Formation, are up to 100m thick and on the western margin of Groote Eylandt, are found within two sub-basins located on the western and southwestern parts of the island, which are separated by a prominent basement divide (Bolton, 1982; Fig. 3). Further inland from the main deposits on the western coastal plain two smaller deposits are located in river valleys eroded into Proterozoic basement quartzites

Correlation between the Cretaceous section exposed on Groote Eylandt and the mainland has been made by Krassay (1994) based largely on the presence of the so-called, C2 marker bed, in both locations. The distinctive C2 marker bed lies immediately below the main ore horizon on Groote and consists largely of kaolinitic- and smectitic (nontronite)- claystone and is found over large areas of east Arnhem Land. The C2 marker bed is considered by Krassay (1994) to be of latest Albian to early Cenomanian.

Figure 5, from Krassay (1994), shows a regional stratigraphic correlation diagram for the East Arnhem Land region. In particular this figure shows the stratigraphic relationships between the various Cretaceous facies described above for Groote Eylandt (under the heading, 'Groote Eylandt Stratigraphic Summary'), and the C2 marker bed. It also shows sections representative of the Cretaceous stratigraphy developed within the Sandfire tenements (under the heading, 'Central Region, Proximal and Distal Outcrops'). The key points to be noted in this diagram include the presence of the C2 marker within the 'Proximal Outcrops' of the Central Region, and the relatively shallow depth of the Proterozoic basement in this region compared to elsewhere in Arnhem Land. Krassay (1994) notes that the Cretaceous sequence in the region of interest is much thinner (condensed) than on other parts of the basin.

6.2.2 Areal extent/size/form/structure

The manganese ores on Groote Eylandt extend over an area of ~50 km^2 as an almost continuous gently dipping (typically <5° dip to west) stratiform bed up to 9m thick (averages 3m thick; Fig. 3). The zone of mineralisation, developed mainly on the western coastal plain of the island, extends for at least 22 km NS and about 7 km EW. Extensions of this mineralisation are known to the north, west, south and southeast to

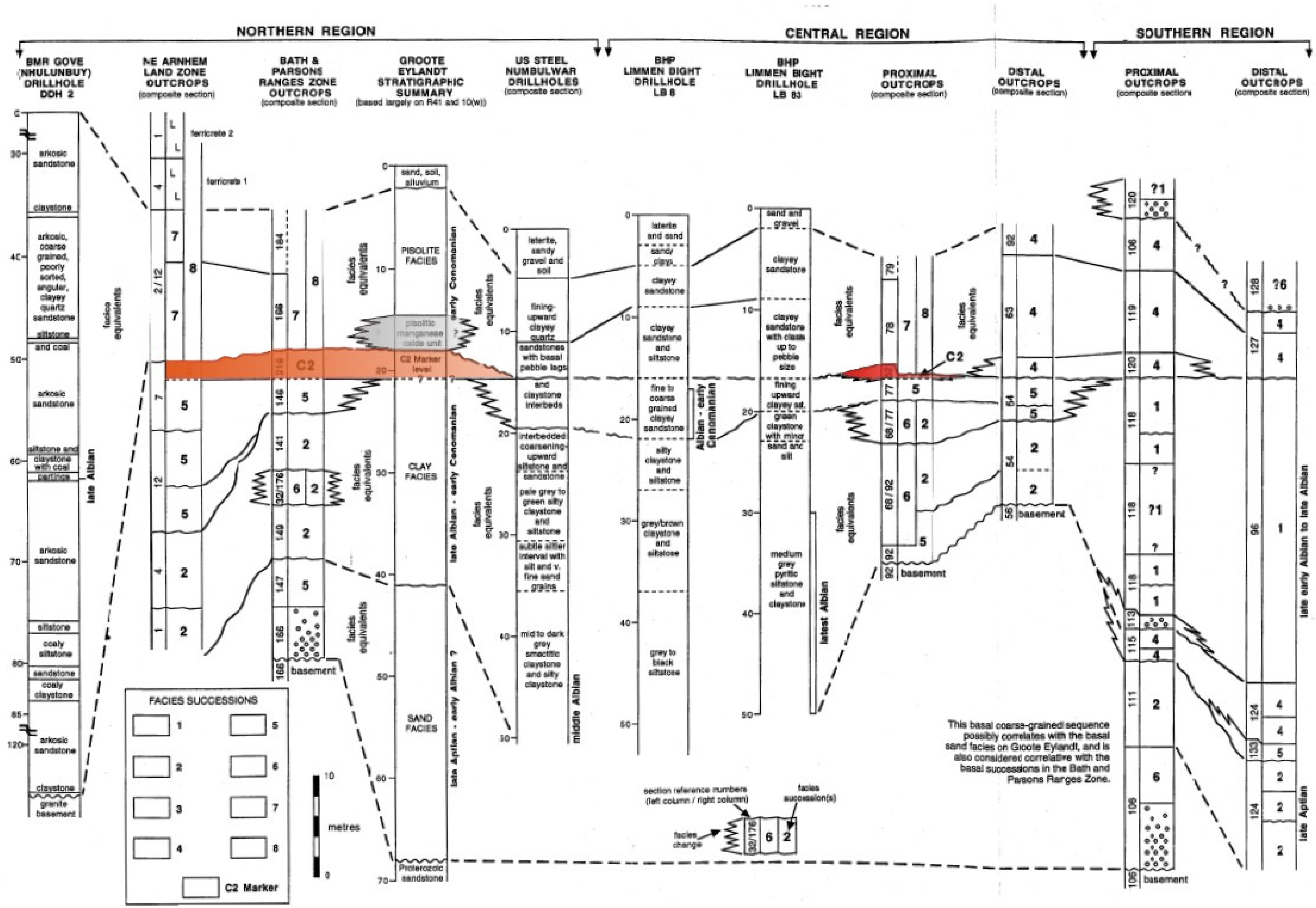

Figure 5. Regional correlation diagram for the western part of Carpentaria Basin. C2 marker bed is highlighted in red and manganese ores on Groote Eylandt is highlighted in grey (from Krassay, 1994)

extend the total known area of Mn mineralisation in this region to in excess of $450km^2$.

The manganese ores on Groote are essentially undeformed apart from gentle warping and minor slumping of beds where they abut rapidly rising Proterozoic basement.

Manganese mineralisation in the Walker River Formation on Groote Eylandt occurs from about 50m above to 50m below present sea level.

6.2.3 Depositional environment and palaeogeography

The mineralisation on Groote Eylandt occurs primarily in the form of pisolites and oolites formed by biologically mediated chemical precipitation, and deposited in a shallow-water, high-energy marine to estuarine environment during periods of peak transgression and early regression (Bolton et al 1990) within a large epicontinental sea that inundated a large area of east Arnhem Land and central Queensland, at that time. A palaeogeographic reconstruction of Groote Eylandt and the adjoining areas of Arnhem Land is given in Figure 6.

The manganese oolites and pisolites and host glauconitic sands, silts and clays are essentially shoreline deposits which onlap a deeply dissected and irregular basement topography. On Groote Eylandt manganese ores occur immediately adjacent to this ancient shoreline. Locally, this style of mineralisation is also developed around elevated Proterozoic basement that at the time of deposition (Late Cenomanian/Early Albian; i.e. ~95 Ma) would have formed prominent islands in the depositional landscape of the time. On Groote Eylandt these ‘islands’ or Proterozoic inliers are fringed by some of the thickest and highest grade manganese ores present in the deposit.

There is also evidence at Groote Eylandt for the coincident deposition of finer grained sediments such as organic- and sulphide-rich silts and clays in more distal, oxygen-depleted marine environments further offshore.

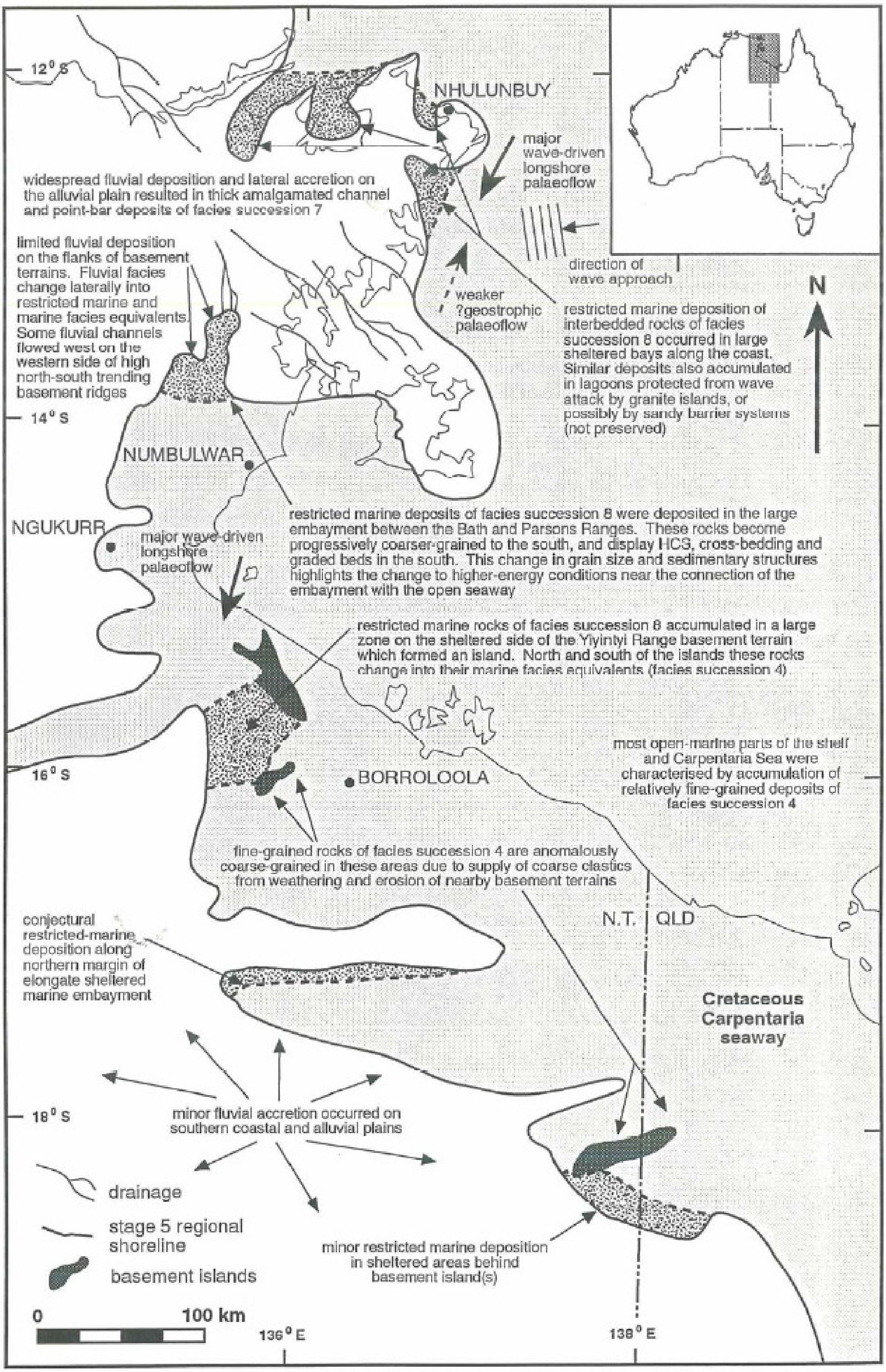

Figure 6. Palaeogeographic reconstruction of East Arnhem Land for the early Cenomanian (from Krassay, 1994)

Evidence for a shallow water, high energy marine environment of deposition for Mn pisolites and oolites is abundant on Groote Eylandt. This evidence includes the accretionary grains themselves, their presence in cm to m scale x-bedded units indicative of wave and storm action, and marine fossils such as dinoflagellates, foraminifera and radiolaria. It should also be pointed out that the foraminifera recovered from these sediments are mostly planktonic foraminifera of the schackoinid group including *Hedbergella delrioensis* and probably *Schackoina cenomanica*. Significantly, this foraminiferal assemblage is considered indicative of a low salinity, possibly estuarine, marine basin of greatly restricted circulation.

While it is clear primary processes lead to the deposition of manganese in concentrations well above those normally found in marine sediments, the making of the Groote Eylandt orebody is in large measure due to, in the first instance, early diagenetic deposition of Mn cements that bound the original accretionary particles together and multiple phases of remobilisation and reprecipitation of Mn in a subaerial supergene environment. K/Ar dating of cryptomelane from a range of sample types gave ages of formation ranging from 21 to 41 Ma (early Miocene to late Eocene) indicates that strong alteration of the deposit occurred at these times (Pracejus, 1989).

6.2.4 Petrology and Mineralogy

A number of textural types exist including uncemented pisoliths and ooliths (the primary sediment), cemented pisoliths and ooliths (resulting from diagenesis) and textureless concretionary ores (essentially the result of secondary, supergene processes). Geologically the uncemented pisoliths and ooliths form the bulk of the deposits.

The primary sedimentary manganese oxide pisoliths and ooliths are composed mainly of pyrolusite (MnO_2), cryptomelane (MnO_2), romanechite ((Ba, K) $Mn_5O_{10}.xH_2O$), todorokite ((Ca, Na, K, Ba, Mn^{2+}) $Mn_6O_{12}.3H_2O$), and to a lesser extent, vernadite ((Ba, K) $MnO_2.xH_2O$), manganite (MnO_2), and birnessite (($Na_{0.3}Ca_{0.1}$ $K_{0.1}$)(Mn^{4+},Mn^{3+})$_2O_4$. $1.5H_2O$). (Pracejus, 1989; Ostwald, 1988). Textureless, concretionary ores are dominated by cryptomelane. Manganese carbonates are also known from the southwestern basin and are composed mainly of manganocalcite ((Ca, Mn) CO_3) and rhodochrosite ($MnCO_3$).

The main gangue minerals include kaolinite, quartz, goethite and small amounts of hematite, smectite and illite.

6.2.5 Geochemistry

Published accounts of the geochemistry of the Groote Eylandt manganese ores are few. Most of the data presented either summarises the geochemistry of the manganese ore products sold (e.g. McIntosh et al 1975) or the composition of the various manganese and gangue minerals observed in the deposit (e.g. Ostwald, 1982; 1988). Only a few provide information on the geochemistry of the manganese ores and their host sediments in a stratigraphic context (Ostwald, 1987; Bolton 1982; Pracejus, 1990).

Ostwald (1987) describes the mineralogy and origin of manganese carbonates s from Cretaceous age calcareous marls in a series of drill hole located in the southwestern part of Groote Eylandt. He concludes that there is little evidence for the formation of manganese carbonates (mainly mangano-calcite) from older manganese oxides by diagensis. Rather, Ostwald proposes that Mn carbonates are mainly the result of primary precipitation in a trangressive marine sequence under moderately reducing conditions. Rare rhodochrosite also found in the section, is interpreted to have formed by recrystallisation of earlier formed mangano-calcite in a diagenetic environment. Ostwald provides very little discussion on the variation in geochemistry with depth other than drill hole samples record a zone of elevated calcium abundance in a seaward thickening wedge of calcareous sediments between 25 and 55m. The calcareous marls and siltstones of this southern basin have been dated as early Cenomanian on the basis of the occurrence of microfossils. The available geochemical data for Groote Eylandt therefore indicates manganese carbonates were deposited close to and at about the same time as manganese oxide deposits.

Bolton (1982) presents the geochemistry of the main pisolitic manganese oxide ore bed for three locations on the western margin of Groote Eylandt. Pracejus (1990) also presents geochemical data for samples collected from vertical sections at various locations across the main Groote Eylandt ore body. The main finding from both studies is that the vertical distribution of major, minor and trace elements is largely the result of the extensive and pervasive supergene processes that have affected the manganese ore beds. The present distribution of elements in the ore body is largely a function of the secondary mineralogy, which is in turn a reflection of the complex interplay between ores, gangue minerals and ground waters present in the host sequence.

Other important geochemical features of the Groote Eylandt section are as follows:

- The deposits are depleted in many of the elements that would normally be expected in conjunction with Mn, e.g. Co, Cu, and Ni. These elements only occur in trace amounts in the deposit;
- Mn/Fe ratios are typically very high throughout the deposit indicating a high degree of fractionation of Mn from Fe in the deposit. The presence of glauconite and pyrite in host sediments indicate a primary separation of these elements in the depositional environment;
- Manganese carbonates probably represent a 'distal', deeper water offshore facies equivalent of the 'proximal' manganese oxides of the main ore body.

6.2.6 Geophysics

The two main geophysical techniques employed at Groote Eylandt are gravity and airborne EM. Gravity was used to provide information on the basement topography and EM was successfully used to provide a means of direct identification of manganese oxides at shallow depth (Irvine & Berents, 2000).

The gravity survey was conducted in 1966 on a widely spaced grid (~1200x60m) and according to Taylor (1967), allowed for 'the subsurface topography to be calculated with reasonable accuracy'. Furthermore, Taylor (1967) indicates that changes in gravity values (1.5 milligals) may be produced by the manganese deposits themselves although he later adds that given the size of these anomalies, no information can be gleaned on the thickness or grade of manganese ores from the gravity data.

The GEOTEM airborne electromagnetic (AEM) survey was flown over the Groote Eylandt manganese deposit in 1991 and proved to be a suitable method for use in explorating for such a deposit 'providing the host rocks are comparatively resistive' (Irvine & Berents, 2000). The moderate to high EM conductivities typical of samples representating all of the main ore types, allowed for the delineation of mineralized zones in areas of shallow cover (to a depth of ~30m).

7. GUIDES TO EXPLORATION

7.1 Introduction

Consideration of the Groote Eylandt model and specifically, palaeogeography, stratigraphy and age place restraints on areas of exploration for manganese in east Arnhem Land and the Borroloola tenements in particular. Below I present a guide to exploration aimed at the discovery of high grade manganese deposits similar to those found on Groote Eylandt.

The following factors are important guides in the design and implementation of an exploration program for manganese in this region:

7.2 Palaeogeography

In general the palaeogeographic configuration should be similar to that at Groote Eylandt. This will require identifying areas that in the first instance, lie to the east (seaward) of the inferred late Albian/early Cenomanian shoreline (Fig. 6). This would at least place the explorer within areas permissive for the presence of a marine sedimentary sequence of palaeogeographic setting to that host to the Groote Eylandt manganese deposits.

It is also important to consider the arrangement of Cretaceous outcrops (and subcrop), with respect to basement highs. The known ores at Groote Eylandt occur in a small ‘embayment’ almost surrounded by Proterozoic highs and very near a shoreline which lay mainly to the east. The planktonic formaniferal assemblage (Schackoinid) from Groote indicates restricted access to the open sea (possibly opening to the south). This situation is almost exactly duplicated on the mainland in several areas including the region bounded by the Yiyinti Range in the northeast, the Costello Range in the west and the Tawallah Range in the south and southeast. This region is shown as an area of restricted marine facies rocks on the palaeogeographic reconstruction by Krassay (1984; Fig. 6). The prospectivity of this region has already been confirmed by the widespread occurrence of sub-economic manganese oxides at shallow depth at localities such as Rosie Creek South and Yitinti. Many small exposures of Cretaceous rocks are mapped within this region and many more probably occur at shallow depth beneath a Cenozoic residual cover. Furthermore, much of this area is at the same level as the Groote Eylandt deposits. Post-depositional movement along the numerous faults that characterise this area would also need to be considered as any movement during the Cretaceous or later, may have resulted in non deposition of the permissive age rocks or their subsequent erosion.

7.3 Age of the strata

It is important to determine as precisely as possible the age of the target stratigraphy. As we have seen above the primary manganese beds at Groote Eylandt were deposited during a transgressive/regressive event dated at late Albian/early Cenomanian. The ore deposit on Groot Eylandt appears to be related to peculiar physical and biological conditions tied to this highstand of sealevel. At present, there is no evidence of manganese deposition during other highstands.

While rocks of Albian/Cenomanian age are abundant in many of the broader Cretaceous epicontinental seaway of which the east Arnhem Land/Groote Eylandt region is a small part, rocks of the target age are relatively rare in many parts of Arnhem Land having apparently being stripped away by erosion after the sea withdrew from the margins of the Carpentaria basin. While it is thought that primary ores accumulated in quiet areas near Proterozoic highs, it is also likely that both primary and secondary ores would have been best preserved where nearby resistant Proterozoic outcrops prevented their subsequent erosion.

Information on the age of Cretaceous rocks of Arnhem Land and the area of interest in particular, is very sparse. Over all of Arnhem Land only some 70 or so samples have been assigned ages in the published literature. Thus the distribution of late Albian strata is at best, only approximately known. In the meantime, exploration for manganese deposits should include collection of fossils (macro and micro) and suitable material for K/Ar or other dating methods.

7.4 Lithofacies

Successful application of the Groote Eylandt model for manganese exploration in Arnhem Land will require detailed knowledge of the lithofacies present and their environment of deposition. The primary oolitic and pisolitic manganese beds found on Groote Eylandt are interpreted to have formed by accretion in a restricted marine basin in very shallow water immediately adjacent to a deeply incised and irregular shoreline composed of stable Proterozoic quartzite. The primary manganese deposits are essentially chemical sediments precipitated in an agitated coastal setting further characterised by low detrital input (i.e. a starved basin receiving very little terrigenous input), and evidence of low salinity, possibly estuarine conditions (e.g. foraminiferal assemblage, woody material found as nuclei).

Identification of glauconite, pyrite and other iron-rich mineral species in the depositional sequence would also provide evidence of an efficient mechanism for primary segregation of manganese from iron and the increased likelihood of elevated Mn/Fe ratios in any manganese deposits found.

The presence of manganese carbonates in the target stratigraphy would provide a local evidence of a partitioning of manganese deposition into more distal, oxygen-depleted environments from nearshore, proximal settings were more abundant oxygen led to abundant precipitation of manganese oxides, largely in the form of accretionary oolitic and pisolitic lithofacies. Detailed petrographic studies of any manganese particles are recommended to confirm an accretionary origin rather than the concretionary forms associated with post-depositional supergene processes.

A consideration of the regional distribution of lithofacies in rocks of the target age, together with an understanding of any trends in geochemical indicators such as Mn/Fe ratio and the presence of manganese carbonates, may provide important clues to the location of potentially economic reserves of high grade manganese oxide ores.

7.5 Geophysics

As noted above, gravity and the application of electrical methods can be effective in the exploration for manganese deposits of the Groote Eylandt type (and elsewhere e.g. Woodie Woodie, WA). The Sandfire tenements in east Arnhem Land are in many areas covered by Cainozoic material thereby reducing the effectiveness of non-intrusive exploration methods. Gravity surveys may provide a rapid means of, in the first instance, gaining essential information on the basement topography and cover thickness, and once prospective areas have been identified, direct detection of high grade manganese mineralisation.

Determining basement topography and detection of the manganese ores themselves might also be obtained through the use of alternative methods such as seismic surveys and ground penetrating radar (restricted to the upper 15m).

Airborne EM (AEM) has been flown over much of the Sandfire tenement holding. It would appear from a the work done by Sandfire to date that exploration planning and identification of drill targets in particular have been focused very much on the identification of conductive AEM anomalies (see discussion above in sections 4 and 5). While this strategy has confirmed the presence of manganese oxides in the areas tested, the correlation between areas of manganese mineralisation and the most conductive anomalies, has been far from convincing (as also pointed out by Hawke, 2009). This finding highlights the limitations of the technique for manganese exploration particularly where the mineralisation occurs in either a conductive host sequence or where the target stratigraphy is underlain by conductive basement rocks. Consideration might be given to commissioning a geophysicist with experience in electrical methods to review all of the geophysical data from the Sandfire tenements and east Arnhem Land generally to advise on any further processing that might be applied to improve the targeting capability of these data or indeed whether alternate methods might be best applied given the results of previous work.

Application of ground-based EM methods, and in particular Moving Loop Transient Electromagnetic (MLTEM) surveys have been successfully used to delineate massive, near-surface manganese oxide ores at several mines and exploration plays including

Consolidated Minerals' Woodie Woodie mine in the East Pilbara. Dipole-Dipole Induced Polarisation (DDIP) surveys have also been successfully used in exploring for high grade manganese oxide ore bodies. The application of both of these techniques is the result of the highly conductive nature of most manganese oxides ores and particularly where supergene processes have been operative.

While not applied to the Groote Eylandt deposit, hyperspectral imagery, either acquired from aircraft (e.g. HYMAP) or satellite (e.g. ASTER), may also be a useful exploration tool. Hyperspectral mapping allows the identification of most species of phyllosilicates, clays, carbonates and metal oxides that occur in the regolith and parent rocks. Manganese oxides have a distinctive low reflectance signature relative to clay and iron oxide minerals. CSIRO in partnership with Curtin University have used these properties to successfully map units at Woodie Woodie, a producing manganese mine in Western Australia.

8. CONCLUSIONS AND RECOMMENDATIONS

This review is presented in three parts. The first, under section 4, provides a number of specific recommendations and findings related to the work done on the Sandfire tenements during the 2008 drilling campaign.

The second part reviews in some detail the essential features of the Groote Eylandt in terms of how they might be applied to manganese exploration in east Arnhem Land. Based largely on these features I then developed a series of guides that might be applied to exploration in this region. The discussion and recommendations presented below relate to this ‘big picture’ view of how best future exploration for economic manganese deposits might be conducted in this highly prospective region.

The main conclusions and recommendations from this evaluation are:

1) Despite the widespread occurrence of manganese oxides in sediments overlying Proterozoic basement within the Sandfire tenements, measured grades and tonnages have fallen below those required for economic exploitation. While it seems likely that additional tonnages can be identified through further shallow drilling at several of the prospects and in particular at Rosie Creek South, I see no reason to expect substantially higher grades will be discovered based on present knowledge of the area and using the past practice of closely spaced drill testing.

Manganese is clearly present across a wide area of east Arnhem Land so the question then becomes one of where to best target future exploration aimed at the discovery of high grade material of sufficient extent to form an economic deposit.

My main concerns regarding the work to date is that it has been over-reliant on identifying and drilling EM targets without an understanding of their geological setting. Palaeogeographic considerations appear to have been limited to the general observation that target areas lie close to basement and are east of the late Albian palaeoshoreline.

<u>Recommendation 1</u>: I recommend a detailed understanding of palaeogeographic setting at the regional through to prospect scale is developed from available information to better target areas for drill testing. This understanding will need to be revised and updated as additional information comes to hand from field mapping, geophysical surveys and future drilling (see below). Favourable areas within the basin include palaeo-estuaries and river channels against basement highs.

2) There is little evidence in recent work by Sandfire that clearly establishes the age, nature and stratigraphic relationships of the post-Proterozoic cover sequences in the region of interest. Confirming the presence of late Albian/early Cenomanian marine sediments of similar age to the mineralizing event on Groote Eylandt is a key requirement in establishing the potential for the region to host economic manganese deposits.

<u>Recommendation 2</u>: It is recommended that all future sampling conducted on the tenements include provision for age determinations to provide temporal constraints on target selection.

3) Establishing the stratigraphic relationships between cover sequences (including consideration of their relative ages, as noted above), and their component lithofacies, is also considered a key element in identifying target areas. For example, the presence of abundant Fe-bearing phases in organic-rich sediments possibly associated with manganese carbonates might be used in conjunction with palaeogeography to point the explorer towards more prospective shallow water, more oxygenated parts of the basin that were more conducive to the formation of high grade manganese oxide precipitation and concentration.

<u>Recommendation 3</u>: It is recommended that future mapping of the region of interest include detailed analysis of litho-facies with particular focus on evidence of lithological, chemical and mineralogical indicators of sea level change and basin stratification similar to that seen on Groote Eylandt.

3) The use of geophysical methods remains an essential requirement in the discovery of economic manganese deposits within the Sandfire tenements. As noted above, airborne EM targets have been the main tool, together with previously reported manganese occurrences, in the identification of drill targets. Other methods including gravity, seismic and electrical techniques have also been successfully applied in search of economic manganese deposits.

Recommendation 4: In addition to a thorough review of the geophysical data recently available for this project, I recommend that consideration be given to acquisition of regional gravity and seismic data aimed at providing detailed information on basement topography under shallow cover and possibly, direct detection of high grade manganese mineralisation.

4) As most areas of interest are likely to be located under shallow cover, drilling will still be required to test for manganese mineralisation. RC drilling has for many years been successfully used at Groote Eylandt in evaluating ore reserves. Boreholes here are located evenly and systematically on a square sampling grid over the mining lease area. Preliminary investigation of the generally flat-lying manganese ores at Groote were done by grid drilling on a 480 m grid. This broadly outlined the extent of manganese mineralisation. In regions where ore-grade rock was intercepted, infill drilling on a 240 m grid was done for more accurate definition. More detailed evaluation of the orebody by increasing drill hole density to 120 m and 60 m grids has since been done for mine planning and quarry grade control.

Additional evaluation of the manganese ores can be achieved, where close to the surface, through the use of bulldozer or backhoe dug costeans, pits and trenches. Ores exposed in costeans could be submitted for metallurgical testing of bulk samples (e.g. 200 kg).

Recommendation 5: To evaluate manganese potential across the Sandfire tenements it is recommended that a variably spaced (1000, 500, 250, 100, 50 m), shallow (25-50 m) RC drilling program be carried out to fully test for the extent, physical and chemical nature of buried/hidden ores. A final decision on drill

spacing and depth should be in part be based on the results of the geophysical and geological mapping programs outlined above.

It is further recommended that during drilling, samples of rock are collected every 0.5 m for accurate and detailed geological logging of physical characteristics (including age) and chemical or metallurgical testing.

9. SOURCES OF INFORMATION

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9.2 Unpublished Material

Most of the information used in this review was supplied by Alastair Barker on a small external hard drive. I understand that all data related to the Sandfire exploration program, together with supporting external data, was included in this data set.

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