NORTHERN TERRITORY GEOLOGICAL SURVEY

PA Ferenczi

IRON ORE, MANGANESE AND BAUXITE DEPOSITS OF THE NORTHERN TERRITORY

REPORT 13

DEPARTMENT OF BUSINESS INDUSTRY & RESOURCE DEVELOPMENT

Northern
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Phil Ferenczi

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DEPARTMENT OF BUSINESS, INDUSTRY AND RESOURCE DEVELOPMENT

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ABSTRACT

Mining and processing of ore from World class deposits of bauxite and manganese have stimulated regional development and made significant contributions to the Northern Territory economy over the last 35 years. Small iron ore deposits have also been mined.

Iron-rich occurrences in the Northern Territory have been classified into four types: oolitic sedimentary, hydrothermal, Fe-skarn and surficial. Mesoproterozoic iron ore deposits of the *Roper River iron field* (McArthur Basin) are examples of the first style. These oolitic ironstones form 0.5-4.0 m thick beds in the Sherwin Formation that are laterally continuous over tens of kilometres. Several hundred million tonnes of ironstone material is present in this region. Ore quality is generally low and typically about 40% Fe, 30% SiO_2 and 0.1% P, although better quality material (>50% Fe, <30% SiO_2 and 0.1% P) exists in the *Hodgson Downs* area. Shallow drilling is required over this area to determine subsurface phosphorus levels. Thin Ordovician oolitic ironstones are present in the Amadeus and Georgina Basins.

Distal hydrothermal iron deposits are massive, tabular to podiform, stratabound hematite ± magnetite bodies formed by the enrichment of an iron-rich protolith. Hydrothermal fluids derived from magmatic or connate brines during orogenic activity have remobilised sedimentary iron in the host sequence into adjacent stratigraphic and structural trap sites. Iron-rich pods in the Frances Creek iron field (Pine Creek Orogen), Tennant Creek mineral field (Tennant Inlier) and Harverson Pass area (Arunta province) are examples of this style of mineralisation.

Some 8 Mt of ore grading 59% Fe has been produced from southern deposits in the *Frances Creek iron field*, which contains series of discontinuous, stratabound, massive hematite lenses over a 40 km strike length. Thick ore intersections (up to 110 m @ 63% Fe) are present in synclinal structures. Small resources exist in the southern (1.4 Mt @ 64% Fe and 0.08% P) and northern (2.4 Mt @ 54% Fe and 0.12% P) areas. Detailed gravity surveys over selected areas in the southern part of the field could be used to detect 1-5 Mt lenses in gently plunging synclinal structures under shallow cover.

Mining of gold and copper over the past 60 years at *Tennant Creek* has produced tailings containing up to 70% magnetite at Warrego (10 Mt), Peko (4 Mt) and Nobles Nob (2 Mt). These tailings represent potential sources of low cost iron ore, as they are located near the Alice Springs–Darwin railway line and existing infrastructure. Small tonnages of iron ore are present in the *Rum Jungle* area and may meet the requirements for other local mineral processing operations.

Small Fe-skarn deposits are present in the Pine Creek Orogen (Mount Bundey area) and Arunta province. Some 840 000 t @ 63% Fe was mined from *Mount Bundey* between 1968-71 and a remaining resource of 190 000 t @ 62% Fe and 0.8% S exists below the pit floor. Surficial Fe occurrences in the NT are not considered an attractive exploration target due to their typical low tonnage and grade.

Manganese occurrences in the Northern Territory have been classified into three types: sedimentary, hydrothermal and surficial. Sedimentary Mn deposits along the western margin of the Carpentaria Basin are the most prospective target. The well documented *Groote Eylandt* deposit with past production of 50 Mt @ 49% Mn and total resources of 212 Mt @ 47.5% Mn, consists of stratiform, massive to disseminated ore in a sheet-like body averaging 3 m in thickness. Manganese minerals were originally precipitated during an early Cenomanian (~95 Ma) marine regression on coastal terraces and troughs.

Exploration by BHP Ltd in places along the southern and western margins of the Carpentaria Basin has identified several mineralised areas, the largest being at *South Rosie Creek*. Areas within the Late Albian shoreline, which have shallow marine sediments but no airborne EM coverage, are considered highly prospective for Groote Eylandt-style Mn.

Hydrothermal (diagenetic) Mn mineralisation has been previously interpreted as surficial in the Renner Springs district (Tennant Inlier). This style of mineralisation is described as stratabound massive replacement deposits in Palaeoproterozoic shallow marine sediments. A 6-12 m thick manganese horizon at the base of the Palaeoproterozoic Bootu Formation can be traced for 24 km around a faulted syncline. Small-scale mining on the western side of the syncline at *Mucketty* produced 13 300 t @ 42% Mn between 1955-69. Drilling on the eastern side at *Bootu 4* by BHP Ltd within a conductive GEOTEM zone, intersected massive Mn mineralisation to 75 m depth. The lower 2 m of the Mn horizon hosts low silica (<10%), high-grade (>40% Mn) ore.

The *Renner Springs* deposits are hosted in siltstone and dololutite near the base of the Palaeoproterozoic Shillinglaw Formation. A percussion drillhole (W38RDH) by Key Resources NL intersected 9 m grading 36.7% Mn including 3 m @ 42.4% Mn from 63 m depth. The resource potential for this Mn horizon is essentially untested. Mn mineralisation at *Wangatinya* (Amadeus Basin) consists of a series of massive bedding concordant lenses averaging about 44% Mn. Surficial manganese occurrences in the NT are widespread and numerous, but appear to be an insignificant resource.

Bauxite occurrences in the Northern Territory are lateritic in origin. These deposits developed during the Tertiary on stable plateaux along the northern coastline. The giant *Gove* deposit with past production of 155 Mt of bauxite grading 50.5% Al_2O_3 and Total reserves of 176 Mt @ 51% Al_2O_3, averages 3.7 m in thickness and has developed over arkosic Cretaceous rocks (Yirrkala Formation). The gibbsitic bauxite is low in silica (3% reactive SiO_2) and is mainly pisolitic and tubular in nature. Profiles through the deposit indicate that some bauxite layers are residual (tubular) while others (loose and cemented pisoliths) have been transported.

Low silica bauxite is present on the *Dhupuma* Plateau (21 km south of Nhulunbuy) which has potential for >35 Mt of untested lateritic bauxite. Several pockets of low silica (4% reactive SiO_2) bauxite totalling 9.9 Mt @ 46% available Al_2O_3 exist on *Marchinbar Island*. These deposits average about 2 m in thickness and rest unconformably on laterite-resistant Marchinbar Sandstone. The bauxite is very similar in composition and character to Gove ore and was probably derived from Cretaceous remnants. Further potential exists in untested bauxite occurrences on *Elcho Island*.

A north sloping lateritic bauxite sheet up to 4 m in thickness has developed along the northern coastline of the *Cobourg Peninsula* and *Croker Island*, over the Cretaceous Bathurst Island Formation. These bauxite deposits are small and relatively low-grade (<35% available Al_2O_3), and have high (>13%) reactive silica. The largest deposit is at *Vashon Head* with 9.7 Mt @ 46.2% Al_2O_3 and 16.1% SiO_2. Further potential exists in Arnhem Land across untested lateritic areas west of *Woolen River*, north of *Peter John River* and in the *King River* area, where Cretaceous sediments overlie Proterozoic granites.

INTRODUCTION

Iron ore, manganese and bauxite (Fe-Mn-Bx) are the raw ingredients used in the manufacture of steel and aluminium, the two most widely used metals that modern society requires for long term economic development. A close commercial and geological link exists between iron ore and manganese deposits. Demand for these two metals is closely tied with global steel consumption and both have similar market specifications, ie lump ore with low phosphorus, silica and sulfur. Large sedimentary deposits of Fe and Mn oxides represent the principal minable sources and exploration targets, despite the large variety of geological host environments. Common exploration techniques (eg gravity and airborne EM) are applicable for both metals. Commercial bauxite deposits are restricted globally in both geological time and distribution, and require a very different exploration strategy.

All three bulk mineral commodities are generally mined from large near-surface deposits. The size required for a deposit to be viable depends largely on its quality and remoteness. The export ore and concentrate producers consist of a few large multinational companies in an industry structure where vertical integration is common, particularly with respect to alumina and manganese. Market requirements of these bulk commodities (eg silica content in iron ore) are an important factor that ultimately determines the capital requirements and in-ground value of any discovered deposits. Ore blending and beneficiation is often required to produce a saleable product. The distance to existing transport infrastructure, a harbour or processing plant are also important factors in determining the viability of deposits. With the impending construction of the Alice Springs to Darwin railway, a review of these commodities in the Northern Territory is appropriate.

World class deposits of bauxite and manganese have played an important role in the Northern Territory economy over the last 30 years. Iron ore has been mined in the past and significant sub-economic deposits exist. Mining projects in the Northern Territory have played a vital role in stimulating regional development and towns such as Nhulunbuy (bauxite and alumina), Alyangula (manganese), Tennant Creek (gold and copper), Jabiru (uranium) and Pine Creek (gold) owe their existence to past and current mining operations.

In the Northern Territory, the mining sector (including alumina production) contributes about 16% to the gross state product (NTDME 2000). Since the development of the Groote Eylandt manganese and Gove bauxite and alumina projects, mining has assumed the role as the Northern Territories largest private sector industry (Hooper 1997). Products from these two operations were valued at $758 M in 1999/00 and this is some $80 M more than the combined value of gold, base metal and uranium mineral production for the same period (**Figure 1**).

Information on location, geological setting, orebody character, ore controls and genesis, past production and resources of iron ore, manganese and bauxite deposits is widely disseminated across unpublished reports and in some published articles. McLeod (1965) presented a brief summary of some significant Northern Territory deposits. A report by Owen (1954) on bauxite in Australia contained information, including geological plans, on several prospects. Publications on Australia's Mineral Resources by the Federal Department of Primary Industries and Energy (and its predecessors) since 1970 summarised the operations and resources of the Gove and Groote Eylandt mines (eg Australia's mineral resources: manganese 1980). A more recent publication on Australia's Iron Ore Resources by Pratt (1993) briefly outlines the geology of deposit types and tabulates known resources.

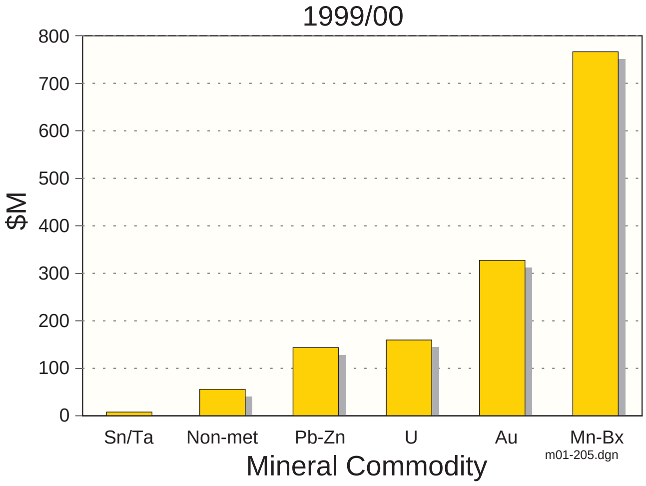

Figure 1. Value of mineral products from mining and refinery operations in the Northern Territory

There are currently 110 iron ore, 126 manganese and 27 bauxite occurrences in the Northern Territory. These are documented on the Northern Territory Mineral Occurrences Database (MODAT) in Microsoft ACCESS, which is available on CD-ROM from the Northern Territory Geological Survey (NTGS). **Appendices 1-3** contain a tabulation of selected details on Fe, Mn and bauxite occurrences derived from MODAT. Information on these occurrences is mainly contained in some 200 company reports, and in publications by the Bureau of Mineral Resources (BMR: now Geoscience Australia) and the NTGS.

The objective of this publication is to summarise the geological setting, ore characteristics, resources and genesis of iron, manganese and bauxite deposits in the Northern Territory for industry and government use. This has been achieved by examining all known company exploration and government reports held within the Northern Territory Department of Mines and Energy (NTDME) and other sites, and by brief field visits to Groote Eylandt, Gove, Bootu Creek, the Roper River and Frances Creek iron fields and Mount Bundey. Some selected petrological work has also been included. Published journal articles on the well-known Groote Eylandt and Gove deposits were largely used to compile their descriptions.

Locations of occurrences and map grid references on some of the figures are Map Grid Australia co-ordinates (MGA) in GDA94. Names of 1:250 000 and 1:100 000 map sheet areas are given in large and small capitals respectively eg URAPUNGA, REYNOLDS RANGE. When referring to total alumina and silica contents of bauxite material, the abbreviations are Al_2O_3 and SiO_2. When referring to available alumina and reactive silica, the abbreviations used are Av.Al_2O_3 and Re.SiO_2 respectively. Geoscientific terms used in this document follow the definitions from Plumb *et al* (1981), Fisher and Warren (1975) and the American Geological Institute's Glossary of Geology (Jackson 1997).

Regional geological framework

This section outlines the regional geological framework of the Northern Territory and specifically focuses on tectonostratigraphic units hosting iron ore, manganese and bauxite mineralisation. Although iron ore and manganese occurrences are widely distributed throughout the Northern Territory (**Figure 2**), bauxite is only known from Cenozoic sediments along the coastline.

Systematic 1:250 000 scale geological mapping covers the entire Northern Territory and some regions are mapped at 1:100 000 scale (eg Pine Creek Orogen and parts of the Tennant Inlier, Arunta province and McArthur Basin). Explanatory notes describing the geology of these map sheets are available for the whole region. A revised Second Edition 1:2 500 000 scale geological map of the Northern Territory has been recently published (Ahmad 2000). Modern, semi-regional (200 to 500 m line spacing) airborne geophysical surveys have been flown by the NTGS and AGSO (now Geoscience Australia) over the past 20 years, and these now cover some 80% of the Northern Territory. Magnetic maps of the Northern Territory at 1:2 500 000 scale have been compiled by Johnstone and Slater (2000) and Clifton (2001). Interpreted or "bedrock" geology maps at various scales have been produced for the Tanami region and TENNANT CREEK.

Geologically, the Northern Territory comprises deformed and metamorphosed Palaeoproterozoic orogenic rocks older than 1800 Ma that outcrop as major tectonic units surrounded by younger rocks (**Figure 2**). These essentially form the recognisable and inferred basement to the North Australian Craton (**Figure 3**). Palaeoproterozoic rocks form the Pine Creek Orogen, Tanami region, northern Arunta province, and Tennant, Murphy and Arnhem Inliers. They include remnants of Archaean rocks that have been dated at 2500 Ma.

Largely unmetamorphosed Palaeo- to Mesoproterozoic (1800-1400 Ma) sedimentary platform covers include the McArthur, South Nicholson and Victoria-Birrindudu Basins, and the Ashburton and Davenport Provinces of the Tennant Inlier. Apart from the Davenport Province, the successions are generally not strongly deformed.

To the south, rocks of the North Australian Craton pass into the Central Australian Mobile Belts where crustal deformation and metamorphism continued until about 500 Ma. These intensely deformed rocks form the Musgrave Block and southern Arunta province. In the southern Arunta province, episodic igneous activity took place between 1880-1050 Ma and deformation included a series of major tectonic events in the Proterozoic and Palaeozoic. The Palaeozoic events also affected the Amadeus Basin succession. The Musgrave Block experienced igneous activity at intervals from 1550-800 Ma and major orogenic events at 1200 Ma and 550 Ma.

In the Amadeus, Ngalia, Georgina, Wiso, Daly and Ord Basins, which cover a large part of the Northern Territory, sedimentation ceased by the Early Carboniferous (about 330 Ma). In the Pedirka, Arafura and Bonaparte Basins, sedimentation continued well into the Triassic (200 Ma). During the Jurassic to Cenozoic period (the past 200 million years) sediments of the Eromanga, Browse, Bonaparte, Money Shoal, Dunmarra and Carpentaria Basins were deposited.

Orogenic Domains (Pine Creek Orogen, Tennant, Murphy and Arnhem Inliers, Arunta province, Tanami region and Musgrave Block)

Intracratonic sediments ranging from fluviatile, shallow marine, evaporitic carbonate sequences to distal facies greywacke, together with interbedded volcanics, represent the extensive orogenic domains of the North Australian Craton. The rocks are tightly folded and metamorphosed to greenschist facies, but may locally reach amphibolite and even lower granulite facies. Syn- to post-tectonic igneous activity includes the intrusion of granitic plutons and basic rocks and the extrusion of felsic volcanics that may be metallogenically important.

Rocks within the Central Australian Mobile Belts, comprising the central and southern Arunta province and the Musgrave Block, consist of granulite and amphibolite facies, metamorphosed sediments and volcanics. The rocks were repeatedly metamorphosed, deformed and intruded by granites throughout the Proterozoic, and were then subjected to further re-activation and retrogressive metamorphism during the Palaeozoic. The Proterozoic events may have taken place in a continental collisional regime, whereas the Palaeozoic events probably took place in an intra-plate setting.

North Australian Platform Cover (McArthur, Victoria-Birrindudu and South Nicholson Basins, Ashburton and Davenport Provinces)

The Palaeo- to Mesoproterozoic sedimentary basins of the North Australian Platform Cover are characterised by accumulations of alternating shallow marine, intertidal, supratidal and fluvial facies, and contain abundant evaporites and carbonates. Mesoproterozoic sediments include shallow marine and fluviatile quartz-rich arenite and subordinate siltstone and carbonate.

Central Australian Platform Cover (Ord, Daly, Wiso, Georgina, Ngalia, Amadeus and Pedirka Basins)

Neoproterozoic to Palaeozoic sedimentary basins of the Central Australian Platform Cover are characterised by shallow marine epicontinental successions of carbonate and marine clastic rocks, evaporite, and fluvial and lacustrine continental sandstone, glaciogenic sediments, shale and siltstone. Extensive sub-aerial flood basalt of Early Cambrian age (540 Ma) covered large areas in the northern part of the Territory.

Neoproterozoic sediments within the Amadeus, Ngalia, Wiso and Georgina Basins are remnants of a once extensive superbasin covering much of central Australia, within which there was some stratigraphic overlap and interfingering of individual successions. These sediments were succeeded by marine carbonate and clastic deposits, which accumulated into Cambrian and Ordovician times (440 million years ago). Younger, non-marine Silurian to Early Carboniferous successions are restricted in areal extent.

The Pedirka Basin contains a Permian-Triassic succession underlying the Eromanga Basin. It consists of terrestrial and in part glaciogenic sandstone, shale and minor coal. It overlies an early Palaeozoic succession comprising Cambrian to Devonian clastic and carbonate rocks of the Warburton Basin.

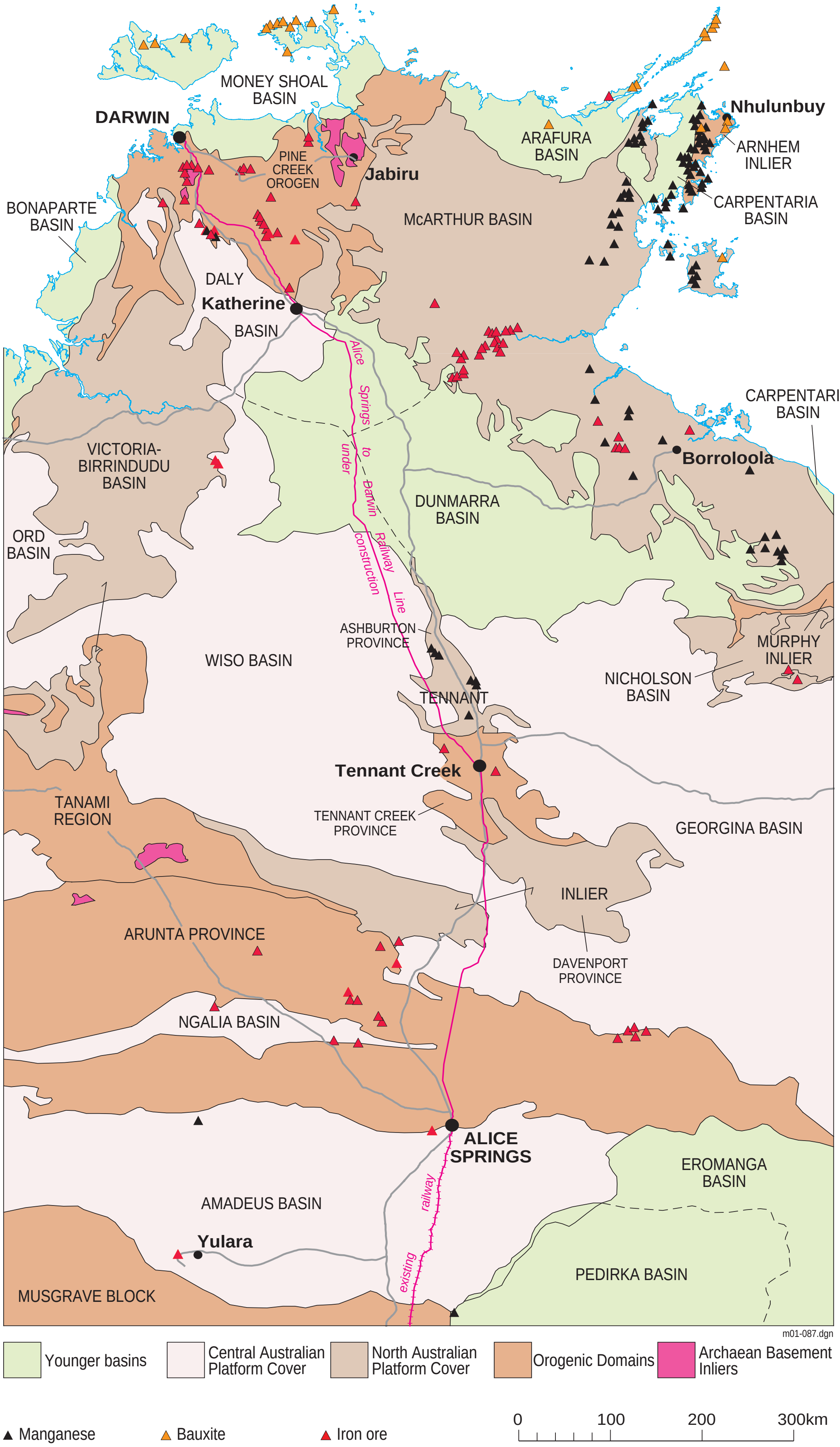

Figure 2. Major geological provinces of the Northern Territory and distribution of Fe, Mn and Bx occurrences

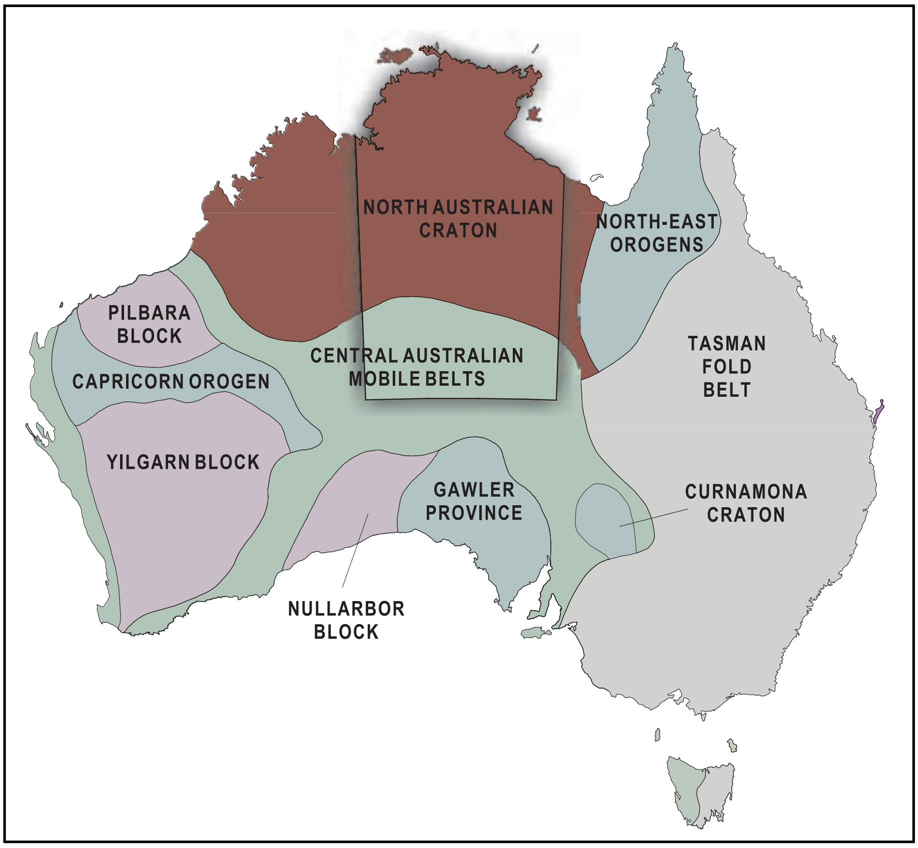

Figure 3. Major crustal sub-divisions of Australia (after Plumb et al 1981)

Younger Basins (Eromanga, Browse, Bonaparte, Money Shoal, Arafura, Dunmarra and Carpentaria Basins)

The onshore Eromanga Basin consists of fluvial, flood plain and lacustrine sandstone, and associated shale and siltstone that are overlain in the southeastern corner of the Territory by marginal marine and thick open marine siltstone. Thin but widespread Cretaceous deposits that are considered to be marine and fluvial in origin also occur in the informally named onshore Dunmarra Basin.

The Arafura and Bonaparte Basins are located mostly offshore and have similar basinal and stratigraphic features. Both basins contain Early Palaeozoic to Mesozoic sediments and developed from rifts in pre-existing sag basins. However, parts of the lower Arafura Basin have been assigned a Neoproterozoic age. The sedimentary rocks consist of mixed terrestrial and marine clastics, marine carbonate and, in the Bonaparte Basin, a marine evaporite succession.

The mostly offshore Browse, Bonaparte, Money Shoal and Carpentaria Basins contain dominantly marine shale and carbonate, and minor sandstone.

Prospective regions

Pine Creek Orogen

Descriptions covering the geology, stratigraphy, metamorphism and structural setting of the Pine Creek Orogen are presented in Walpole *et al* (1968), Needham *et al* (1980, 1988), Stuart-Smith *et al* (1993) and Ahmad *et al* (1993). The metamorphosed and deformed Palaeoproterozoic succession is unconformably overlain by the relatively undeformed Palaeo- to Mesoproterozoic McArthur Basin to the east and by the Victoria Basin to the west and southwest. Phanerozoic strata cover the sequence toward the south and north. Stratigraphic correlations based on previous studies are summarised in **Figure 4**. The simplified geology showing iron ore and manganese deposits is given in **Figure 5**.

Archaean (>2500-2700 Ma) granite and metamorphics are exposed near Batchelor (Rum Jungle and Waterhouse Complexes) and Jabiru (Nanambu Complex). They are also intersected in drillholes near Woolner (Woolner Complex). These Archaean rocks are unconformably overlain by Palaeoproterozoic strata consisting of an alternating sequence of sandstone, mudstone and minor carbonate rocks and volcanics. Dolerite sills (Zamu Dolerite and equivalents) intruded the sequence prior to deformation and metamorphism. The orogenic sequence is constrained between 2470 Ma and 1870 Ma (Page *et al* 1980).

Regional metamorphism and deformation, during which the strata were tightly folded and faulted, followed sedimentation. Regional metamorphic grades range from sub-greenschist facies in the centre to upper amphibolite facies along the western (Litchfield Province) and eastern (Alligator Rivers Region) margins. This period of deformation and metamorphism is known as the Nimbuwah Event of the regionally extensive Barramundi Orogeny and is constrained at 1880-1850 Ma (Page 1997).

A felsic magmatic event (Cullen Event) at 1830-1820 Ma followed the regional metamorphism and deformation (Jagodzinski and Wyborn 1997). Coincident extensional tectonics in the southeast (South Alligator Valley) produced narrow northwest-trending grabens. Two unconformity-bounded successions (El Sherana and Edith River Groups) of sediments and volcanics were deposited in these grabens (Friedmann and Grotzinger 1994).

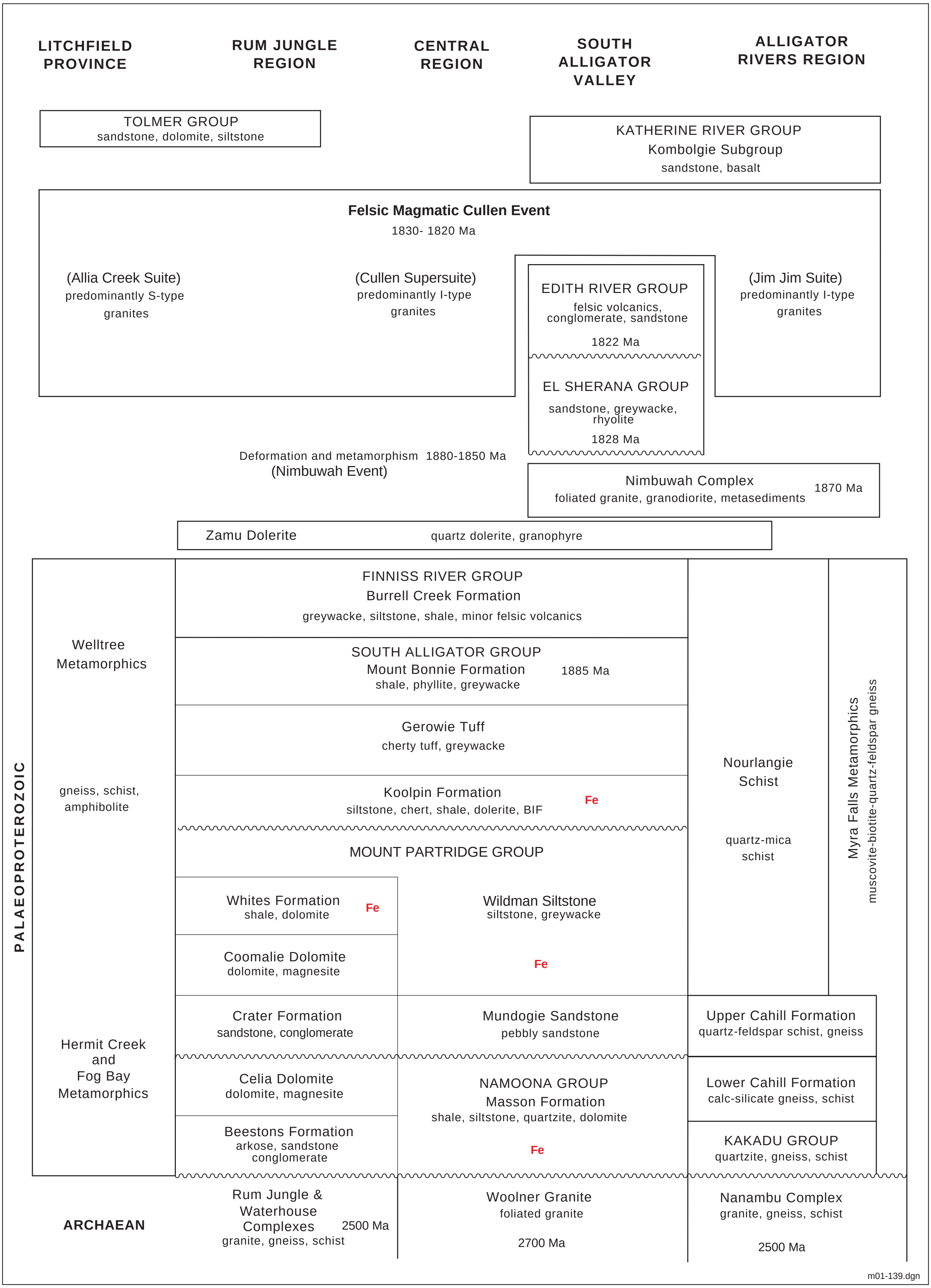

Figure 4. Schematic Proterozoic stratigraphy of Pine Creek Orogen, showing stratigraphic distribution of iron ore and manganese mineralisation (modifed from Needham and DeRoss 1990)

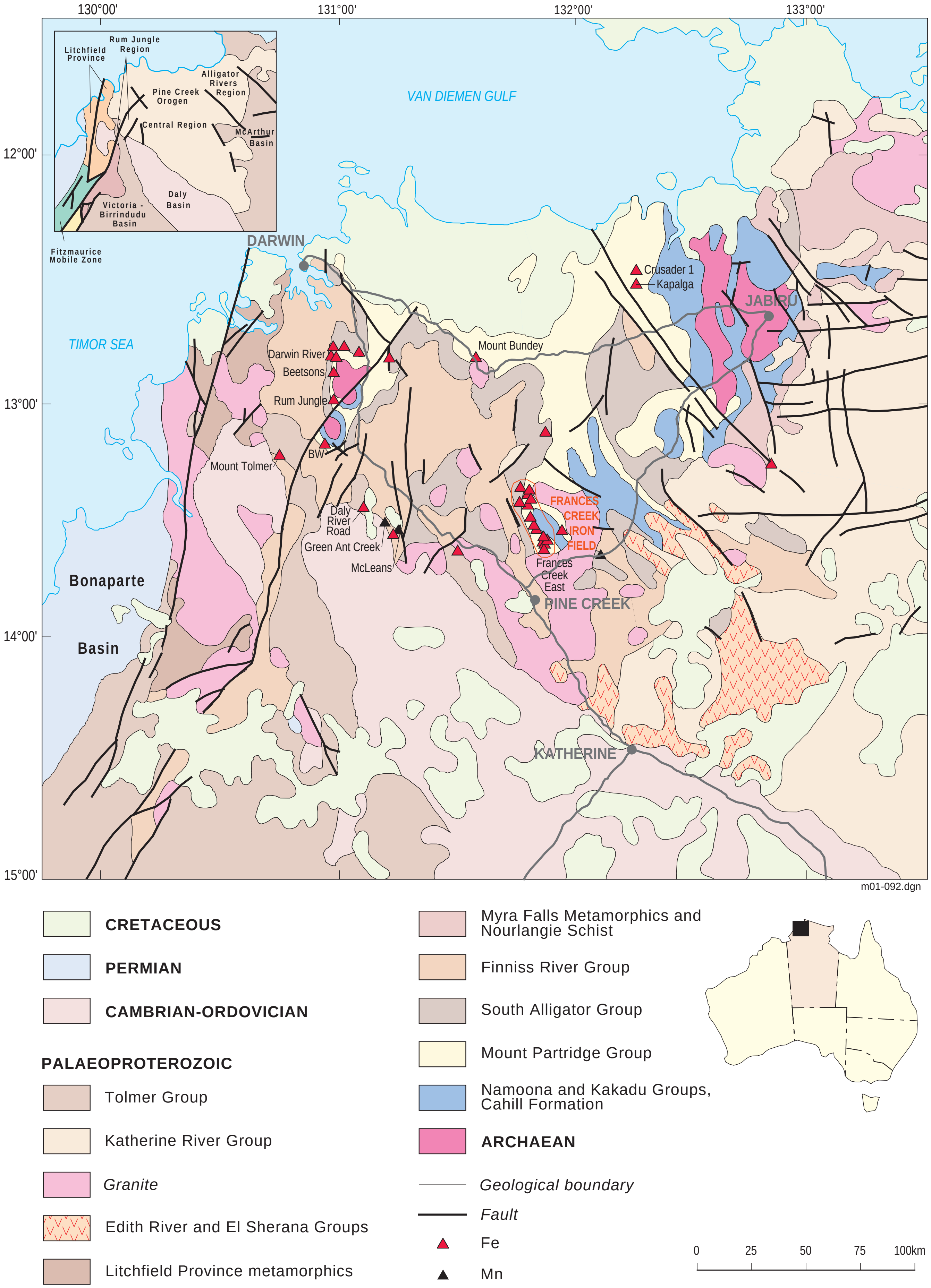

Figure 5. Regional geology and location of Fe and Mn deposits in Pine Creek Orogen

Iron ore has been mined in the past from hydrothermal magnetite-rich pods at Mount Bundey and a series of low temperature hydrothermal hematite-rich stratabound lenses at Frances Creek. Both types are hosted within ferruginous and carbonaceous pelites assigned to the Wildman Siltstone. Surficial iron deposits are also present in various ferruginous pelite units (eg Koolpin Formation) in the orogenic sequence.

Tennant Inlier

Three distinct informal provinces are recognised in the Tennant Inlier. These are, from north to south, the Ashburton, Tennant Creek (previously referred to as Tennant Creek Block by Le Messurier *et al* 1990) and Davenport provinces (**Figure 2**). The Palaeozoic Georgina and Wiso Basins flank the Tennant Inlier to the east and west respectively.

Mendum and Tonkin (1976), Compston (1995) and Donnellan *et al* (1994, 1999) discussed the geology, stratigraphy and structure of the Tennant Creek province. The stratigraphy (**Figure 6**) and generalised interpretative geological map (**Figure 7**) are largely based on the work of Donnellan *et al* (1995, 2001). A polydeformed flysch succession (Warramunga Formation, 1860 Ma), intruded by syn-orogenic granite and granodiorite as well as by felsic porphyry sills, represents the oldest rocks exposed. This package is overlain by felsic volcanics and volcaniclastics (Flynn Group, 1845-1820 Ma), and is intruded by anorogenic felsic intrusives (granite and porphyry) and lamprophyre.

A succession of greywacke, siltstone and mudstone with interbedded felsic and hematitic shale comprises the Warramunga Formation. Deformation of the Warramunga Formation during the Barramundi Orogeny produced moderate to tight upright folds with a pervasive, subvertical east-west slaty cleavage and was accompanied by lower greenschist facies metamorphism. Remobilisation of iron oxides in the sequence probably occurred during early

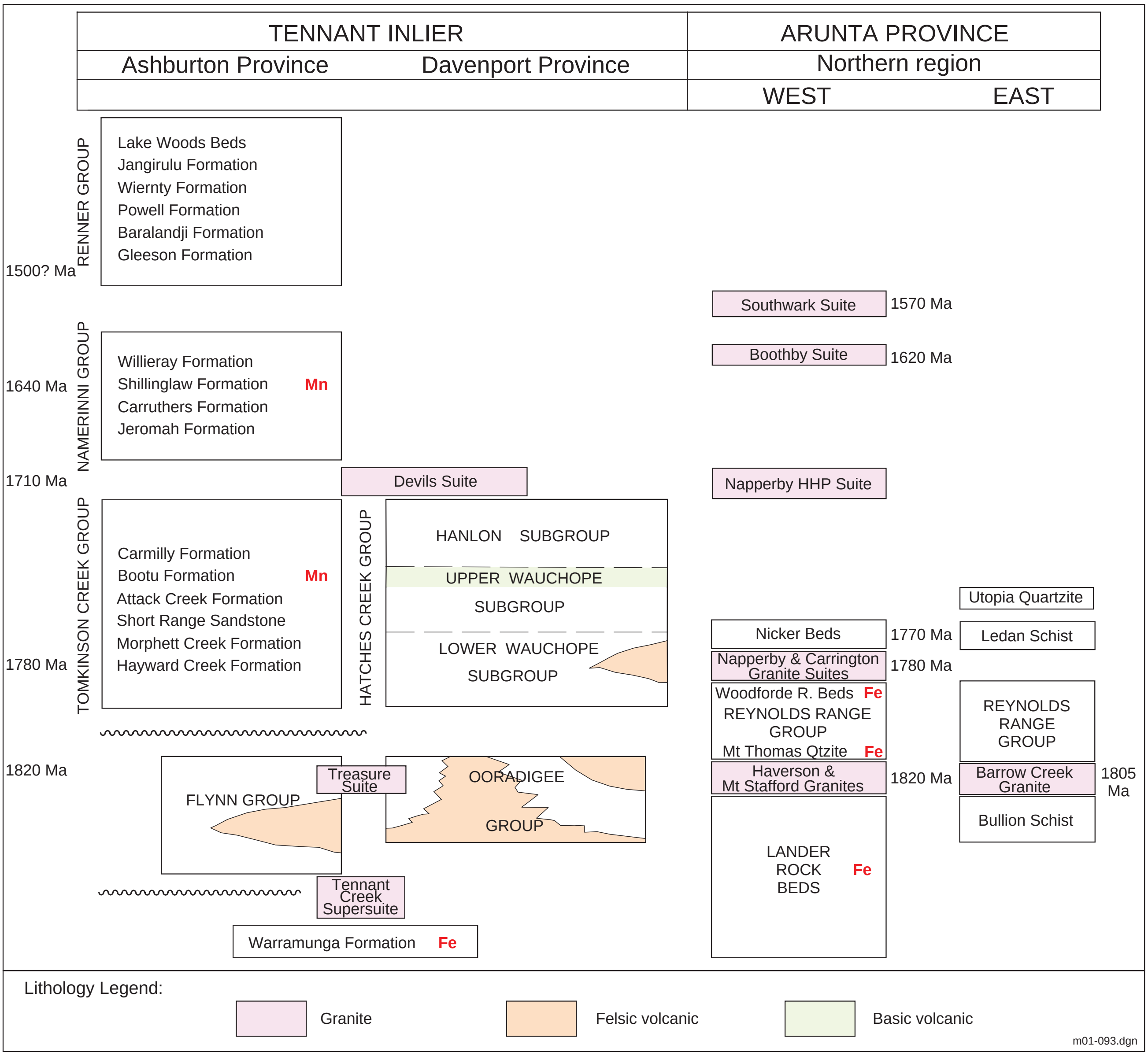

Figure 6. Schematic Proterozoic stratigraphy and correlations between Tennant Inlier and northern Arunta province, showing stratigraphic distribution of iron ore and manganese mineralisation (modified from Donnellan *et al* 2001)

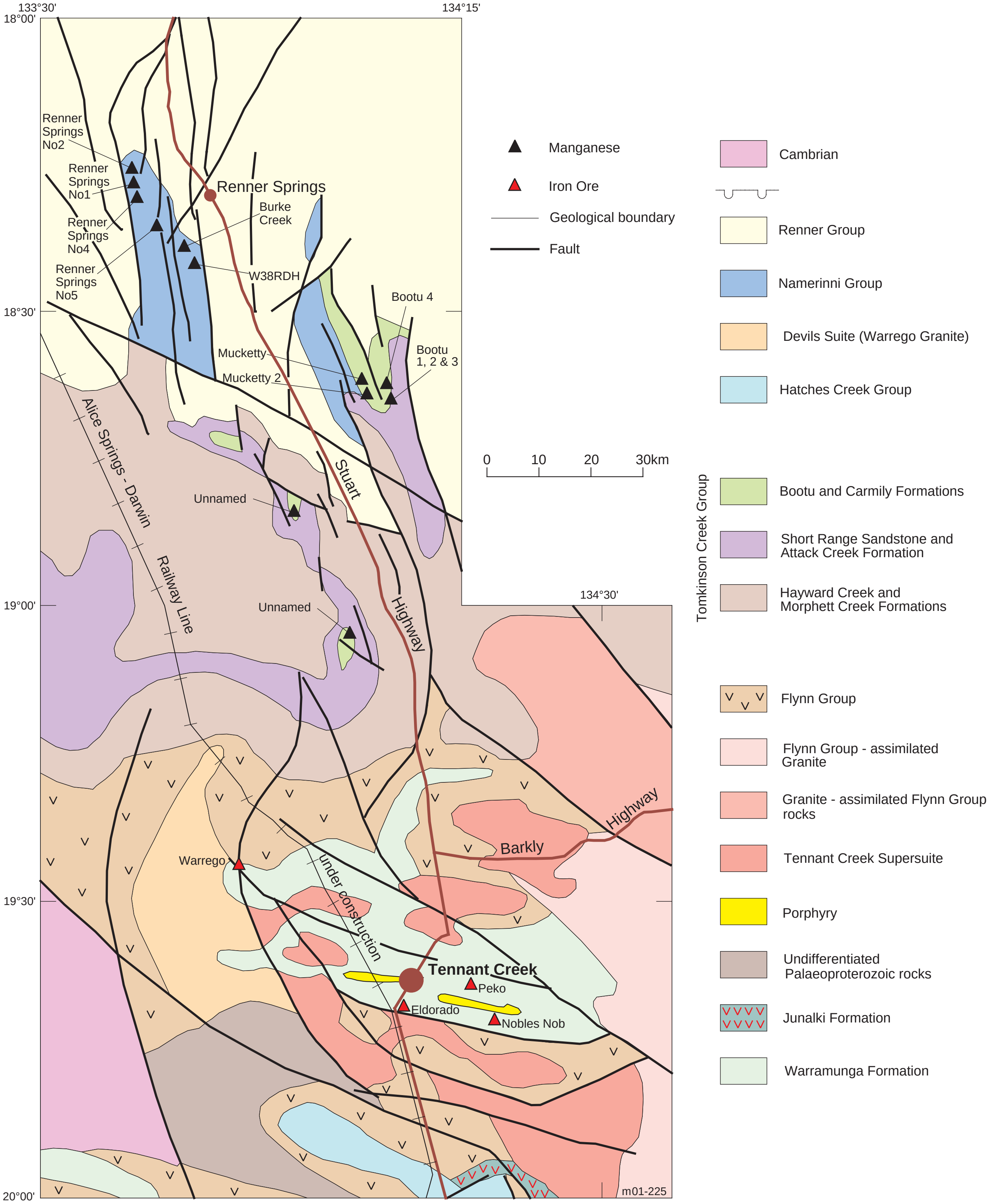

Figure 7. Proterozoic geology and location of Fe and Mn deposits in Tennant Inlier

deformation and the intrusion of early granites. Iron oxides were then concentrated into structural and stratigraphic traps to form magnetite-rich pods, lenses and pipe-like bodies.

I-type granodioritic melts and granitic differentiates (Tennant Creek Suite) intruded the Warramunga Formation and lower parts of the Flynn Group between 1850 Ma and 1840 Ma during the Barramundi Orogeny. Deposition of the volcano-sedimentary Flynn Group and emplacement of the Treasure suite (1830-1825 Ma) followed the Barramundi Orogeny. These mainly volcanic rocks are characterised by predominantly high-K rhyolitic to rhyodacitic lava, felsic tuff and ignimbrites (Donnellan *et al* 1995).

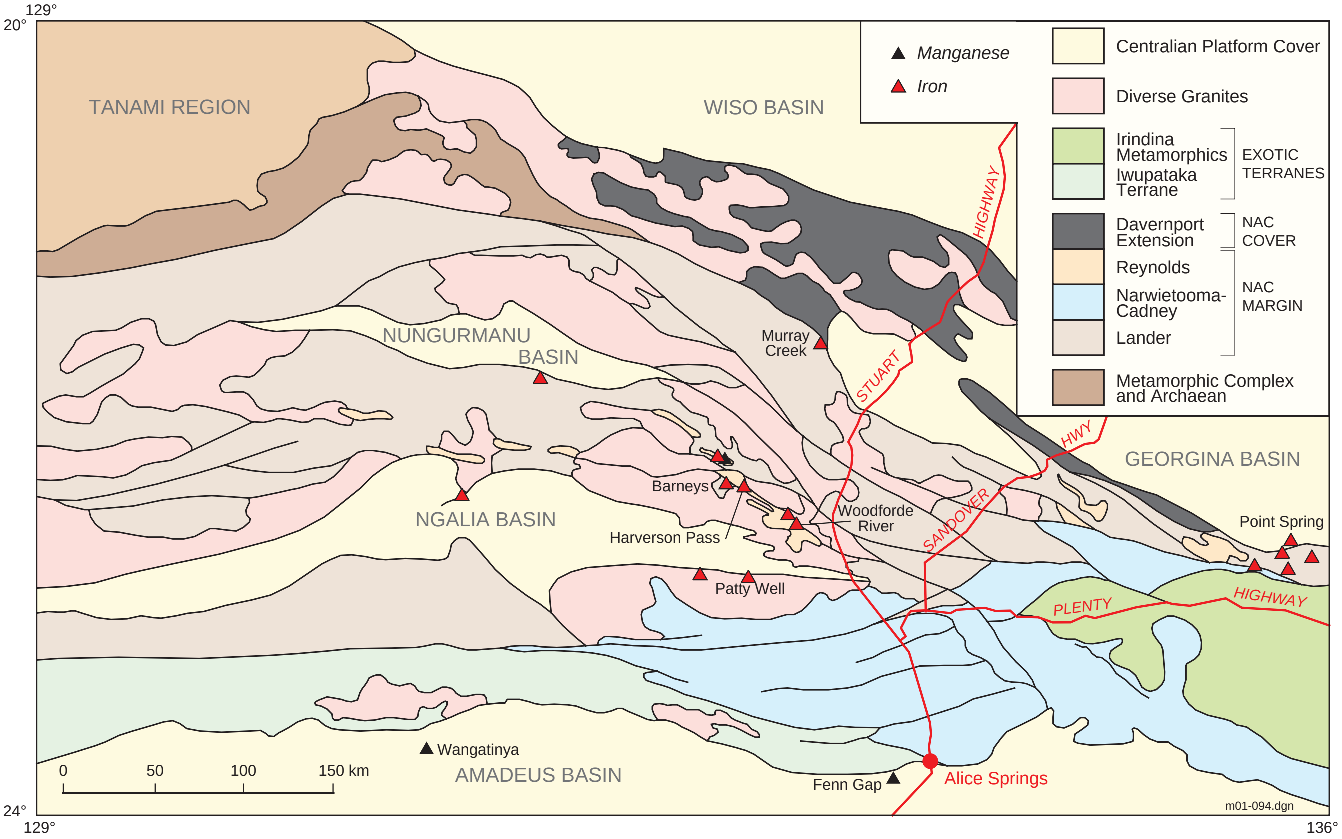

Figure 8. Regional geology and location of Fe and Mn occurrences in central Australia (modified from Gee 2001)

Three unconformity-bounded, predominantly cyclic fluvial to shallow marine sandstone, siltstone and carbonate successions (Tomkinson, Namerinni and Renner Groups) overlie the Flynn Group and comprise the Ashburton province (Hussey *et al* 2001). Continental flood basalts are present in the lower part of the Tomkinson Group. A recessive sequence of calcareous siltstone and stromatolitic dololutite (Attack Creek Formation, 1730 Ma) is present in the upper part of the group.

Overlying this unit is a predominantly ridge-forming sandstone sequence (Bootu Formation) that contains an extensive manganese horizon near the base, within dolomitic siltstone and medium sandstone. This horizon was mined in the past at Mucketty and has significant economic potential. A second manganese horizon is present within siltstone near the base of Shillinglaw Formation (1640 Ma) in the Namerinni Group. This horizon is largely untested and is likely to have a similar genesis to the Bootu horizon. The overlying Renner Group comprises predominately cyclic fluvial to shallow marine sandstone and siltstone.

The Davenport province largely consists of an arenite, conglomerate, siltstone, mudstone, shale and carbonate succession containing interbedded lava and pyroclastics that was deposited into a large, subsiding intracratonic basin (Blake *et al* 1987). Sandstone, mudstone and interbedded subaerial felsic to mafic volcanics comprise the Ooradidgee Group, which has been correlated with the Flynn Group to the north (Donnellan *et al* 2001). The overlying Hatches Creek Group is subdivided into two subgroups (Wauchope and Hanlon Subgroups). These represent a similar style of sedimentation to the Ooradidgee Group, but with reduced volcanism in the Wauchope Subgroup. The Hanlon Subgroup represents an eventual transgression of the basin by shallow marine sediments. The sequence within the Davenport province was intruded by sills of gabbro, dolerite and granophyre prior to deformation (Strangways Orogeny, 1770 Ma) and was subsequently intruded by post-tectonic granites (1710 Ma). There are no manganese, iron ore or bauxite occurrences known from the province.

Arunta province

Details of the geology, stratigraphy, metamorphism and structural setting of the Arunta province are presented in Shaw *et al* (1984), Stewart *et al* (1984), Hand *et al* (1992) and Collins and Shaw (1995). This province is an intercontinental polymetamorphic belt that covers an area of 200 000 km^2. It is overlain by Neoproterozoic to Palaeozoic Central Australian Platform Cover (Amadeus, Ngalia, Georgina and Wiso Basins). Geochronological, geochemical, structural and geological studies, in conjunction with airborne geophysical surveys undertaken across the province by the NTGS and various universities in the past decade, have led to new regional insights (**Figure 8**).

The three subregions (Northern, Central and Southern) and rock unit Divisions (1, 2 and 3) outlined by Shaw (1990) have been superseded by new stratotectonic packages (Pietsch 2001). The Lander Rock Beds and equivalents consist of mainly turbiditic clastic metasediments and amphibolite that have been variably metamorphosed from greenschist to granulite facies (Young *et al* 1995). The unconformably overlying Reynolds Range Group contains a package of shallow marine quartzite, calc-silicate and pelitic schist (Stewart 1982). Iron ore occurrences are present in the Lander

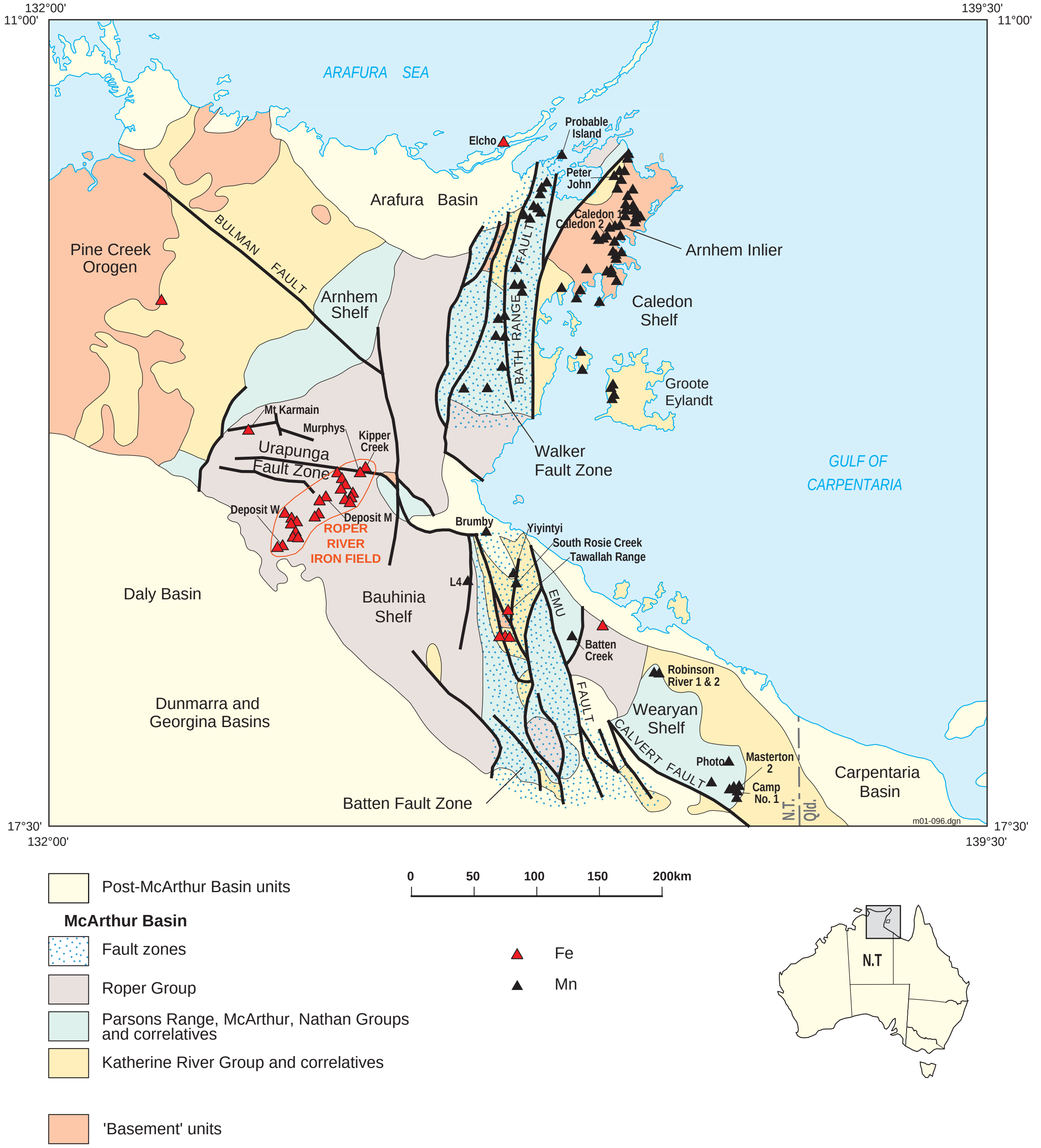

Figure 9. Regional geology and location of Fe and Mn deposits in McArthur Basin

Rock Beds and in the lower part (Mount Thomas Quartzite) and upper part (Woodforde River Beds) of the Reynolds Range Group (**Figure 6**).

Numerous regional and localised orogenic events have been identified by Collins and Shaw (1995) in the Arunta province, including the Yuendumu Tectonic Event (1880 Ma), Stafford Tectonic Event (1860-1820 Ma), Strangways Orogeny (1730-1780 Ma), Argilke Tectonic Event (1680 Ma), Chewing Orogeny (1660 Ma), Anmatjira Uplift Phase (1450 Ma), Tinpot Magmatic Event (1140 Ma) and Alice Springs Orogeny (300-400 Ma). These events represent a composite picture and are not recognised throughout the entire province.

Syntectonic granites ranging in age from 1880 Ma (Atnarpa Suite) to 1140 Ma (Tin Pot Suite) have intruded the province (Warren and Shaw 1995, Wyborn *et al* 1997). The largest intrusive phase took place at around 1770 Ma (Napperby Suite). At 1200 Ma, this province was intruded by the Mordor Igneous Complex (Langworthy and Black 1978). Igneous activity in the Arunta province ended at 730 Ma with the intrusion of the Mud Tank Carbonatite (Black and Gulson 1978).

McArthur Basin

The Palaeo- to Mesoproterozoic McArthur Basin is an intracratonic platform basin with an areal extent of 200 000 km^2. This basin unconformably overlies metamorphosed and deformed sequences of the Pine Creek Orogen to the west, Murphy Inlier to the south and Arnhem Inlier to the east (**Figure 9**). The Murphy Inlier was a palaeogeographical high separating the McArthur Basin from the South Nicholson Basin and Lawn Hill Platform (Plumb 1987). In the Batten and Walker Fault Zones, some 12 km of shallow water sediments were deposited compared to about 4 km on the Arnhem, Bauhinia, Caledon and Wearyan shelves (Plumb *et al* 1990).

Stratigraphic correlations across the McArthur Basin are given in **Figure 10** and are largely based on Rawlings (1999). The basal units are represented by "transitional domains" (1830-1820 Ma) of igneous activity and sedimentation that followed deformation of the Pine Creek Orogen and equivalent strata. The overlying Katherine River Group and equivalents (1815-1710 Ma) consist of fluvial to shallow marine arenite and conglomerate alternating with lutite and basic volcanics. Minor felsic volcanics, shallow intrusives, carbonate and shale are also present in the sequence. These sediments were deposited throughout the McArthur Basin during an extensional event (Plumb 1994). In most areas, a well marked angular unconformity separates this package from the overlying McArthur Group and equivalents. However in the Walker Fault Zone, arenite deposition (Parsons Range Group) continued without a break into the overlying Habgood and Balma Groups (Pietsch *et al* 1994, Haines 1994).

The McArthur Group and equivalents (1670-1600 Ma) include stromatolitic-evaporitic carbonate alternating with shale, siltstone and minor sandstone. Deposition of this group was largely confined to the Walker, Urapunga and Batten Fault Zones. The overlying Nathan Group and equivalents (1600-1570? Ma) consist of a mainly stromatolitic and evaporitic carbonate (eg Karns Dolomite) and sandstone sequence, which was deposited in a broad shallow-water to marginal marine sag basin. Local development of surficial manganese concentrations is common in the Karns Dolomite.

Following major uplift, erosion and basin-wide regolith formation, the cyclic arenite and lutite sequence of the Roper Group and equivalents (1490-1420 Ma) were deposited on a basin-wide scale. Sedimentary oolitic ironstone is present at several intervals within the Roper sequence and is best developed within the Sherwin Formation.

Arafura Basin

The Arafura Basin is a pericratonic basin that covers an area of about 500 000 km^2. It extends northward from the Northern Territory coastal fringe into and beneath the Arafura Sea (**Figure 2**) and contains a sequence of Neoproterozoic and Palaeozoic sediments that were deposited under predominately shallow marine conditions. Petroconsultants (1989) suggested that the boundaries of the basin are the Merauke Rise in the north, Aru ridge (west), Wessel Rise (east) and McArthur Basin (south). Within the Arafura Basin is the northwest trending Goulburn Graben, which is some 400 km long and up to 85 km wide. This contains up to 10 km of Palaeozoic sediments, whereas the northern and southern platforms have 5-3 km of sediment preserved, respectively (Bradshaw *et al* 1990).

The stratigraphy has been established from several offshore petroleum wells, marine seismic data and onshore geological mapping. Neoproterozoic shallow marine sandstone, mudstone and minor carbonate rocks of the Wessel Group comprise the oldest rocks in the Arafura Basin. On Marchinbar and Elcho islands, several bauxite deposits unconformably overlie the Marchinbar Sandstone (Wessel Group). Surficial iron deposits have developed in the overlying Elcho Island Formation on Elcho Island. These rocks are disconformably overlain by Cambro-Ordovician carbonate sediments of the Goulburn Group.

Nearshore marine siltstone, sandstone and shale of the Devonian Arafura Group were subsequently deposited on eroded Cambrian and Ordovician strata. Ungrouped Permo-Carboniferous sediments comprising a basal limestone unit, deltaic siltstone and paralic to marine pyritic siltstone and limestone are unconformably overlain by Mesozoic sediments of the Money Shoal Basin. Regional tilting and uplift, which may have triggered or accentuated extension within the Goulburn Graben, is thought to have occurred in the Late Palaeozoic (Petroconsultants 1989).

Carpentaria Basin

The Carpentaria Basin is a broad, north-trending intracratonic basin covering an area of about 600 000 km^2, about 20% of which is in Northern Territory waters. Most of the basin lies offshore within the Gulf of Carpentaria. The basin was formed as a gentle intracratonic downwarp in the Jurassic and Cretaceous and contains up to 1760 m of mainly Mesozoic clastic sediments (Burgess 1984). McConachie *et al* (1990) subdivided the basin into four sub-basins that are recognised by the characteristics of the basal Mesozoic sandstone or the basement they overlie (**Figure 11**).

Onshore in the west, the basin is flanked by Proterozoic rocks of the Arnhem and Mount Isa Inliers and the McArthur Basin, which the shelf succession overlies with angular unconformity. Basement highs separate the Carpentaria Basin from the Papuan Basin in the north and Eromanga Basin in the south.

The stratigraphy of the Carpentaria Basin has been established from eight onshore petroleum wells, several water bores, marine seismic data and one offshore petroleum well. Deposition commenced in the Jurassic with fluvial sandstone, minor siltstone and conglomerate in a series of basement depressions. Fluvial sandstone deposition was widespread during the Early Cretaceous.

A Middle Cretaceous marine transgression brought paralic and then widespread shallow marine conditions to the basin, resulting in the deposition of a thick mudstone sequence. Pisolitic manganese was precipitated in protected coastal areas along the west coast of Groote Eylandt at this time. A late Middle Cretaceous regression resulted in the return of paralic conditions and deposition of the Normanton Formation.

The Western Gulf Sub-basin is characterised by rugose basement palaeotopography and thin to absent basal Mesozoic sandstone. Fine marine sediments of the Rolling Downs

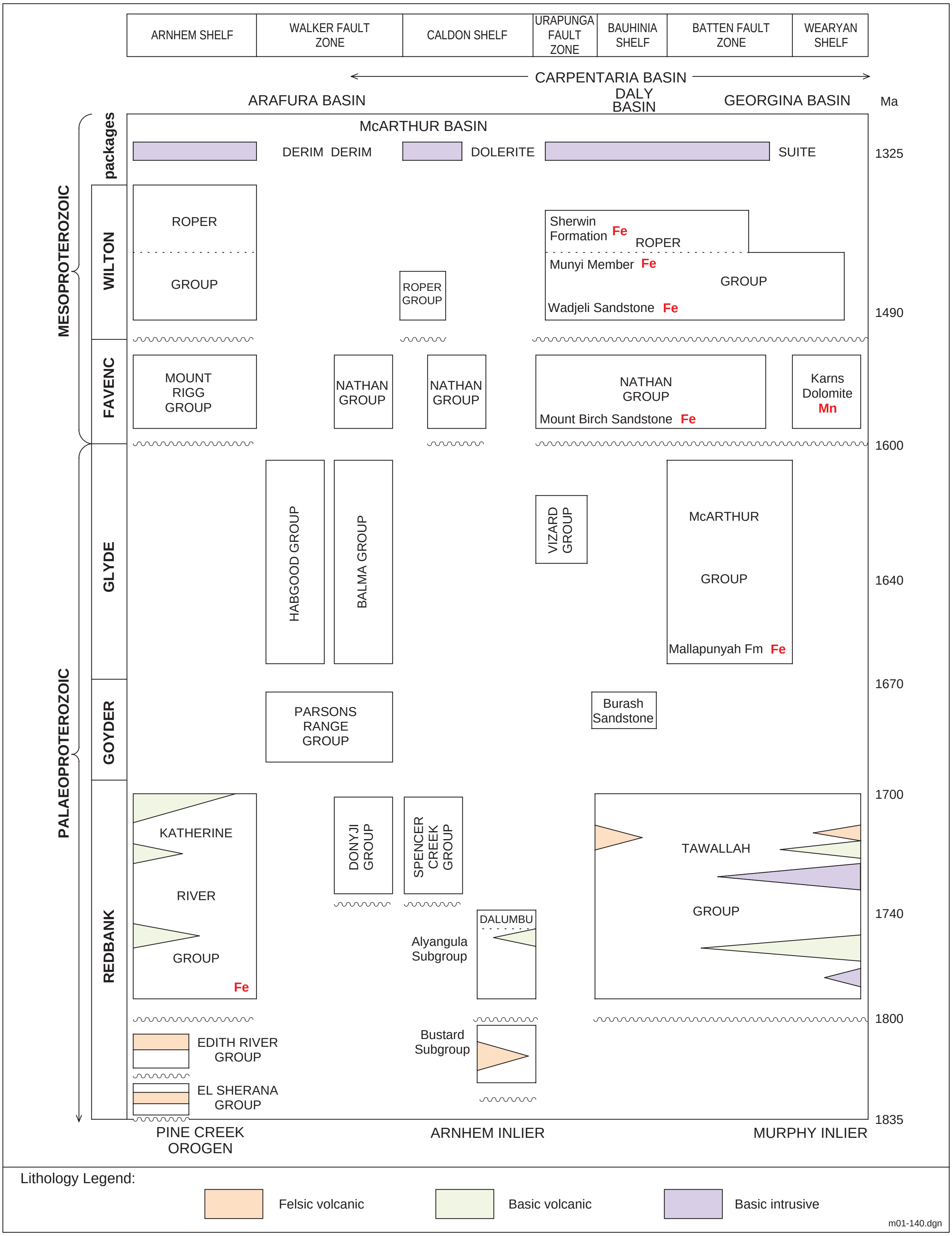

Figure 10. Schematic Proterozoic stratigraphy of McArthur Basin, showing stratigraphic distribution of iron ore and manganese mineralisation (modified from Rawlings 1999)

Group constitute the bulk of the stratigraphic section in this sub-basin, which suggests that this part of the basin consisted of highlands with contemporaneous isolated valleys, infilled during the Jurassic-Early Cretaceous (McConachie *et al* 1990). Cretaceous strata of the onshore Western Gulf Sub-basin consist of a thin sequence (max 100 m) of sandstone,

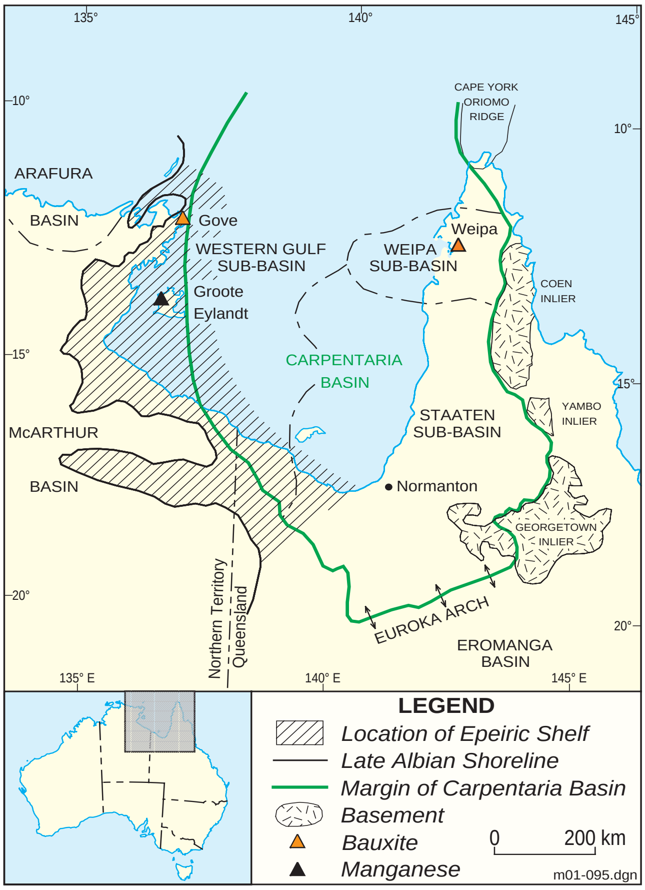

Figure 11. Carpentaria Basin showing locations of major manganese and bauxite deposits (modified from Krassay 1994a)

siltstone and conglomerate, which is preserved as mesas and plateaux in a 150 km wide belt along the western margin of the Gulf of Carpentaria (Krassay 1994a). This belt represents the western epeiric shelf of the Carpentaria Basin and the extent of the Late Albian western shoreline (**Figure 11**).

During the Early to Middle Cretaceous, storm- and wave-dominated siliciclastic sediments accumulated on this gently sloping shelf. The sequence has been studied by Krassay (1994b) who subdivided the previously named Mullaman Beds into the shallow marine, manganese-bearing Walker Creek Formation and the mainly fluvial Yirrkala Formation. Extensive bauxite deposits have developed over the latter on the Gove Peninsula.

Money Shoal Basin

The Money Shoal Basin is a pericratonic basin covering an area of about 350 000 km^2, most of which lies offshore in the Arafura Sea (**Figure 2**). It developed as an embayment after continental plate break-up and divergence along the northwest margin of Australia in the Jurassic, and contains mainly Mesozoic clastic and Cenozoic carbonate sediments up to 4500 m thick (Petroconsultants 1989). The Money Shoal sequence unconformably overlies the Palaeozoic Arafura Basin. It is flanked by the Pine Creek Orogen and McArthur Basin to the south, and is bounded by the Wessel Rise in the east and by the Moyle River Fault zone in the west.

The stratigraphy of the Money Shoal Basin has been established from numerous petroleum exploration wells, stratigraphic drillholes, marine seismic data and onshore geological mapping (Hughes 1978, Mory 1988, Petroconsultants 1989). Deposition commenced in the Jurassic with marine silt (Frigate Shale) and sand (Sandpiper Sandstone) prograding over basal fluvial sand containing minor coal in the east (Plover Formation).

A mid Cretaceous marine transgression brought paralic sand (Darwin Formation), followed by widespread shallow marine conditions that resulted in the deposition of micaceous mud and shoreline sand (Wangarlu Formation and Moonkinu Sandstone) of the Bathurst Island Group (Mory 1988). Cenozoic sediments are represented by the fluvial to paralic Van Diemen Sandstone, which is exposed on Bathurst and Melville Islands, and shelf carbonates to the west and north. Sub-economic bauxite deposits have developed over the Bathurst Island Formation along the northern coastline of the Cobourg Peninsula and Croker Island. Minor manganese has been reported in the Moonkinu Sandstone in the vicinity of Murgenella Wildlife Sanctuary (Hughes 1978).

IRON ORE

Definition and classification

Iron constitutes about 5% of the Earth's crust, making it the fourth most abundant element. Iron oxides and hydroxides form the principal iron ore minerals, due to their high iron content and occurrence as large tonnage surface deposits. Almost 300 minerals contain some iron, but only a few are considered to be important ore minerals (**Table 1**). Nearly all of the mined iron ore (98%) is used in iron and steel production.

Mineral	Chemical Composition	% Fe (Max)	SG	Hardness
Hematite	Fe_2O_3	70	5.1	5-6
Magnetite	Fe_3O_4	72	5.2	5.5-6
Goethite	$Fe_2O_3.H_2O$	63	4.3	5-5.5
Lepidocrocite	γ-$Fe_2O_3.H_2O$	60	4.1	5
Limonite	$Fe(OH).nH_2O$	60	3-4	5-5.5
Siderite	$FeCO_3$	48	4	4
Pyrite	FeS_2	46	4.9	6-6.5
Chamosite	$(Fe,Mg,Al)_6$ $(Si,Al)_4O_{14}(OH)_8$	42	3.1	3
Greenalite	$Fe_3Si_2O_5(OH)_4$	45	2.9	3

Table 1. Properties of iron ore minerals

Iron is a tough, malleable, magnetic metal and forms important alloys with silicon, manganese, chromium, molybdenum, titanium, aluminium, carbon, nickel and tungsten to enable manufacture of a great variety of useful metal products (Sully 1987). Steel, an alloy of iron and carbon, is the dominant metal commodity due to its unsurpassed versatility, relatively low production cost and availability of raw materials. Iron is also used in gas and water purification systems and in the manufacture of magnets, pigments (eg ochre), abrasives (eg magnetite as a dense medium in coal washing) and high density concrete.

Iron ore may be defined as natural material of suitable grade, composition and physical quality that can be mined

Table 2. Classification of iron ore deposits (modified from Pratt 1993)

Genetic category	Geological setting/ ore-type	Iron ore minerals	Grade (Fe %)	Examples
A. SEDIMENTARY				
BIF	Superior-type (shallow shelf)	magnetite, hematite, siderite	20-40	Hamersley Range (WA), Mesabi Range (USA)
	Algoma-type (volcanic arc, rift)	as above	20-40	Michipicoten Basin (Canada), Pilbara district (WA), Carajas Ranges (Brazil)
	Rapitan-type (fault-scarp basin)	as above		Jacadigo (Brazil), Mackenzie Mtns (Canada)
Oolitic	Clinton-type	hematite, chamosite, greenalite, siderite, goethite	30-50	Birmingham (USA), Constance Range (QLD), Roper River (NT)
	Minette-type	siderite, berthierine, chamosite, goethite	20-40	Lorraine Basin (France), Dawsonvale (QLD)
Placer	Palaeochannel- and detrital-types	goethite, hematite	30-65	Robe River (WA), Yampi Sound (WA), Taharoa (NZ)
Bog iron	Black band siderite	siderite	15-35	Vares (Yugoslavia), Midland Valley (Scotland)
B. IGNEOUS				
Magmatic segregation.	Bushveld Fe-Ti-V	titaniferous magnetite	30-50	Taberg (Sweden), Bushveld (South Africa)
Skarn		magnetite	40-60	Biggenden (Qld), Mount Bundey (NT), Marcona (Peru)
C. HYDROTHERMAL				
Proximal (replacement)	Kiruna-type (volcanic-hosted)	Magnetite (low Ti), hematite	50-65	Kiruna (Sweden), Pea Ridge (USA), Candelaria (Chile)
Distal (Fe enrichment)	Fe sediment-hosted	Specularite, magnetite, goethite	30-65	Koolyanobbing (WA), Frances Creek (NT), Tennant Creek (NT), Marquette Range (USA)
D. NATURAL ENRICHMENT				
Laterite		Goethite, hematite	20-40	Scott River (WA)
Meteoric		Hematite, martite	55-70	Mt Tom Price (WA)

and processed for profit or economic benefit (Gross 1993). Iron ore deposits are widespread and have formed in a range of geological environments throughout geological time. Pratt (1993) has divided iron ore deposits into four major categories based on their mode of origin, using aspects of previous classifications by Gross (1970) and Klemic *et al* (1973):

- Sedimentary (Banded Iron Formation, oolitic, placer, swamp);
- Igneous (magmatic segregations and skarn);
- Hydrothermal (proximal and distal); and
- Surficial enrichment (laterite and supergene).

This four-fold classification can be further subdivided on the basis of geological setting and recognised ore-types (Table 2).

Sedimentary deposits

Sedimentary deposits, particularly those in Banded Iron Formation (BIF), contain the bulk of the world's iron ore resources. Sedimentary iron formations generally form in a variety of marine environments and rarely in continental (coal) swamps (Kimberley 1989a). BIF-hosted deposits are almost exclusively of Precambrian age and are distributed worldwide. An extensive body of data indicates that BIFs form by volcanogenic or hydrothermal effusive processes (Gross 1993), but the origin of BIF-derived iron ore deposits is still debated widely (Morris 1998, Powell *et al* 1999). The most recent publications on the Hamersley deposits suggested that post-depositional hydrothermal enrichment processes played a significant role in the formation of high-grade hematite orebodies (Barley *et al* 1999, Taylor *et al* 2001). BIFs are classified into two types: the Superior-type, which formed in a near-shore continental-shelf environment in association with dolomite, quartzite and shale, and the Algoma-type, which are associated with volcanics (Edwards and Atkinson 1986).

Oolitic deposits are Proterozoic to Cretaceous in age and were an important source of iron ore before 1970. They are lower in grade (30-50% Fe) relative to BIF-hosted deposits (55-65% Fe). Two types have been identified: the Clinton-type consists of deep red to purple ores composed of hematite, chamosite and siderite; the Minette-type consists of brownish to dark greenish-brown ores composed mainly of siderite and iron silicates (berthierine and chamosite). These deposits formed in shallow marine environments and accumulated along passive continental margins during times of quiescence, extension and global sea level change (Van Houten and Hou 1990).

Igneous deposits

Igneous deposits are formed either by magmatic segregation of an immiscible magnetite-rich melt in association with layered mafic-ultramafic intrusions or by injection of magnetite-rich fluids into surrounding rocks (eg Fe skarns). The former occur as massive cumulate-textured seams and are often mined for their economic concentrations of titanium and/or vanadium (eg Bushveld Complex, South Africa). Fe skarns (or pyrometasomatic deposits) are mainly derived from granitic to mafic intrusives and can be hosted in a variety of rock types. These deposits are massive, irregularly shaped to tabular bodies that continue to be a source of iron ore in some countries (eg Peru and Russia).

Hydrothermal deposits

Hydrothermal iron ore deposits are formed by the circulation of heated, iron-rich aqueous solutions of magmatic, metamorphic or sedimentary parentage. These deposits form the basis of most Iron Oxide Copper Gold (IOCG)-style deposits (Hitzman *et al* 1992, Porter 2000). Proximal hydrothermal deposits (also known as volcanic-hosted magnetite deposits) are essentially magnetite-hematite bodies that have replaced non-ferruginous host rocks (eg Kiruna iron ores). These deposits usually have obvious magmatic signatures and adjacent wallrocks are generally intensely altered (Pollard 2000). Hematite-bearing quartz veins within fault zones are also part of this group. Distal hydrothermal deposits are tabular to podiform, stratabound, specular hematite ± magnetite bodies that formed by the enrichment of an iron-rich protolith.

Surficial enrichment

Surficial enrichment of iron ore deposits results from subaerial weathering processes of generally low-grade ferruginous protore, commonly BIF. Mature laterites develop under a wet tropical climate (see introduction to *Bauxite*) and can form extensive duricrust horizons (ferricrete), rich in iron oxyhydroxides. Supergene enrichment of low-grade iron deposits essentially leaches silica and other deleterious constituents and concentrates the iron oxide minerals to produce high-grade ore that can be directly shipped. Fine earthy hematite and iron oxyhydroxides such as goethite, limonite and lepidocrocite are the principal iron minerals produced from surface and near surface enrichment processes.

This classification system is a useful guide but transitions exist between groups and most deposits have undergone more than one Fe enrichment phase. Many BIF-hosted deposits have undergone varying degrees of hydrothermal and supergene enrichment/alteration, so as to produce high-grade ore (>60% Fe). The importance of surficial enrichment (see Pratt 1993) has been overshadowed by recent studies on some iron ore provinces (Hamersley Basin, Australia and Mesabi Range, USA), which suggested that enrichment of BIFs is largely due to the activity of tectonically-induced hydrothermal brines (Taylor *et al* 2001, Morey 1999).

Globally, identified iron ore resources are very large (74 000 Mt) and are distributed throughout many countries. However, some 71% is concentrated in the CIS, Australia, China and the United States (**Table 3**). Iron ore resources in the CIS, China and the United States are mainly low-grade (<40% Fe) and require beneficiation before smelting. Major deposits of naturally enriched BIF are present in Australia, Brazil and South Africa. Sixty five percent of iron metal is mined from four countries: Brazil, Australia, CIS and China (**Table 3**).

Three international companies, BHP-Billiton, Rio Tinto and CVRD dominate the iron ore trade. These companies mine high-grade deposits in Australia (BHP-Billiton, Rio Tinto) and Brazil (CVRD). Iron ore exports are largely based on long term contracts and prices are quoted in US cents per long dry tonne unit (eg a 65% Fe ore is valued at 65 times the unit price). Over 90% of Australia's iron ore resources and 96% of total ore production in 1999 was derived from Western Australia, largely from the Hamersley Basin (AGSO 2000). Pratt (1993) has outlined the geology of the main deposit types in Australia and tabulated known resources. The Northern Territory has a demonstrated paramarginal iron ore resource of 5 Mt and an inferred subeconomic resource of 400 Mt (Pratt 1993).

Exploration and evaluation

Sedimentary deposits represent the most prospective exploration targets for economic concentrations of iron ore and are the favoured sources of this commodity due to their lower content of deleterious elements relative to ore derived from skarn and igneous deposits. Thick Precambrian BIF sequences containing Hamersley-style deposits are preferred to oolitic sedimentary and distal hydrothermal deposits as exploration targets. BIF deposits are commonly preserved in the forelands of Proterozoic orogenic belts and have a wide global distribution (Gross 1993), but are constrained in geological time (Late Archaean to Late Proterozoic). The other types are widely distributed throughout geological time.

Economic iron ore deposits are generally large in tonnage (20-500 Mt) and near the surface. They generate significant geochemical and geophysical expressions. Geological mapping and remote sensing methods such as airborne geophysics, satellite imagery and hyperspectral mapping are used at a regional level to identify prospects. McKenna (1982) outlined the exploration approach and evaluation methods used by Hamersley Iron Ltd in the Hamersley Basin in the 1980s. Various authors in Misra and Dunlop (1997) have described more recent exploration and evaluation methods.

Geological mapping

Geological mapping is used with an airphoto base to determine the distribution and thickness of outcropping or subcropping iron formations and ironstone lenses. Mapping of major and minor fold and fault structures that provide pathways for mineralising fluids can be a key part of an exploration strategy (Tyler and Thorne 1994). Mapping of variations in iron facies and the extent of igneous intrusives are also essential to elucidate the geological controls on iron ore distribution. Regional traverses at 0.5-1 km spacing are generally undertaken using helicopter and four-wheel-drive vehicles.

Airborne geophysics.

Magnetite-rich BIFs and skarns exhibit characteristic magnetic properties that make aeromagnetic surveys the most cost effective method of reconnaissance exploration for these deposits. To enhance effective exploration, Symons *et al* (1981) and Clark and Schmidt (1994) have highlighted the magnetic properties and signatures of Algoma-type iron-formations in Ontario and BIFs in the Hamersley Basin and Yilgarn Craton, respectively.

Table 3. Countries with significant iron ore resources and production (source: Kirk 2000, 2001)

Country	Fe (metal) resource (Mt)	Ore grade (% Fe)	Fe (metal) production 1999 (Mt)	Av Ore grade 1999 (% Fe)
CIS	27 500	55	78.3	58
Australia	11 000	61	94.9	61
Brazil	4800	63	114.2	60
China	7800	31	63.0	30
United States	3000	64	36.5	63
Canada	1100	65	22.0	64
Sweden	2200	63	11.5	62
India	1800	64	43.5	64
South Africa	650	65	18.4	62
Other	11 200	59	50.7	54
TOTAL	71 000	53	533.0	54

The enrichment of BIFs alters magnetite to hematite and this often results in a subdued response in the aeromagnetic data. Reduced magnetic responses in BIF units can also result from other factors (eg intense weathering in fault zones). In the Pilbara Craton, aeromagnetics proved to be useful in the identification of fault structures and dolerite dykes that are known to localise mineralisation, and this led to the discovery of the Yarrie Y2 deposit (Kerr *et al* 1994).

Airborne gravity can be used to identify dense packages and pods within BIF, siliciclastic and carbonate sequences. An airborne gravity gradiometer system developed by BHP Ltd, the FALCON system (van Leeuwen 2000), has been trialed over BIF-style iron ore deposits in the Middle Back Ranges with some success (URL: http://www.bhpbilliton.com/Bp/falcon/dataMiddleback.asp). Ground penetrating radar has been used in the Hamersley Basin to map detrital iron or 'canga' deposits with some success (Butt and Flis 1997).

Satellite imagery

Satellite imagery can be used to map outcropping or subcropping iron-enriched rock types and related vegetation. Fraser (1991) used the visible to near infrared band passes (0.4-1.1 mm) of Landsat Thematic Mapper (TM) images to map the surface distribution of hematite and goethite in the Mount Newman region. The distribution of these minerals at this scale was largely controlled by landscape processes rather than bedrock geology (Fraser 1991).

Hyperspectral mapping

Hyperspectral ground reflectance data can be collected from a conventional airborne geophysical platform (Hausknecht *et al* 2000) or from satellites (eg JERS and ASTER). Commercial airborne sensors such as OARS (Operational Airborne Research Spectrometer), HYMAP, GEOSCAN and AMS (Airborne Multispectral Scanner) allow the identification of iron oxide species that are present in the regolith and primary rocks. Spectra of iron oxide minerals are shown in **Figure 12**. Ratios can be generated over selected band-widths (eg difference between reflectance values at 0.5 μm and 1.0 μm for hematite) where the spectral signature of the targeted mineral is unique relative to other minerals likely to be present in the surface environment.

Regional reconnaissance is followed up by systematic mapping (at 1:10 000-40 000 scale), sampling of natural surface exposures and drilling. Ground geophysical surveys, such as magnetics and gravity, can be used to provide additional insights as to the orientation, shape, size and depth of deposits. Seismic reflection surveys have been used successfully in exploration for new BIF-hosted deposits in the Marquette Range, Lake Superior district, USA (Edwards and Atkinson 1986). Reconnaissance drilling may start on a 230 m by 60 m grid (eg Mount Whaleback) or 100 m by 60 m grid (eg Frances Creek) depending on: 1) the geological model, 2) cost factors, and 3) the exploration strategy of the company.

Diamond drilling is used in preliminary evaluation to gain information on ore types, structure, geophysical properties and to obtain samples for metallurgical test work. Reverse circulation (RC) and percussion drilling are carried out in most drilling campaigns due to the hardness of iron oxide minerals and good sample recovery rates. Down hole gamma logging is routinely applied in the Hamersley Basin for stratigraphic correlation purposes (Dentith *et al* 1994). Drillhole spacing is reduced to 120 m or even 30 m for resource evaluation, then to 20-60 m for ore reserve and mine planning, depending on orebody size, structural complications and ore quality variations.

Sampling intervals for drillhole material can be 0.5–2 m, depending on the average thickness of the ore zone. Drill material is normally split and half is sent for chemical analysis for the following constituents: FeO, Fe_2O_3, SiO_2, Al_2O_3, P_2O_5, MnO, S, C, V, TiO_2, CaO, MgO, K_2O, Na_2O, loss on ignition (LOI) and trace elements. Once the main impurities in the deposit under evaluation and the customer specifications are known, this list can be substantially reduced.

Samples are usually analysed by X-Ray Fluorescence (XRF) or Inductively Coupled Plasma Spectroscopy (ICP). Most iron ore operations establish an onsite XRF laboratory to provide low cost, timely, multi-element analysis for quality control and mine planning. X-Ray Diffraction (XRD) and optical electron microscopy can provide information on mineralogical composition. Bulk samples from representative sections of the orebody, which can be obtained from diamond drillholes, adits or shafts, are required for metallurgical investigations. Misra (1997) has outlined the main laboratory test methods for determining the metallurgical characteristics of iron ores.

When assessing the economic potential of a deposit, important factors are tonnages of ore, Fe content, mineralogy, impurities, beneficiation characteristics, the type of iron- and steel-making process to be used and transport costs. Iron ore specifications depend on its intended commercial application, which can be metallurgical (eg cast iron, structural steels and

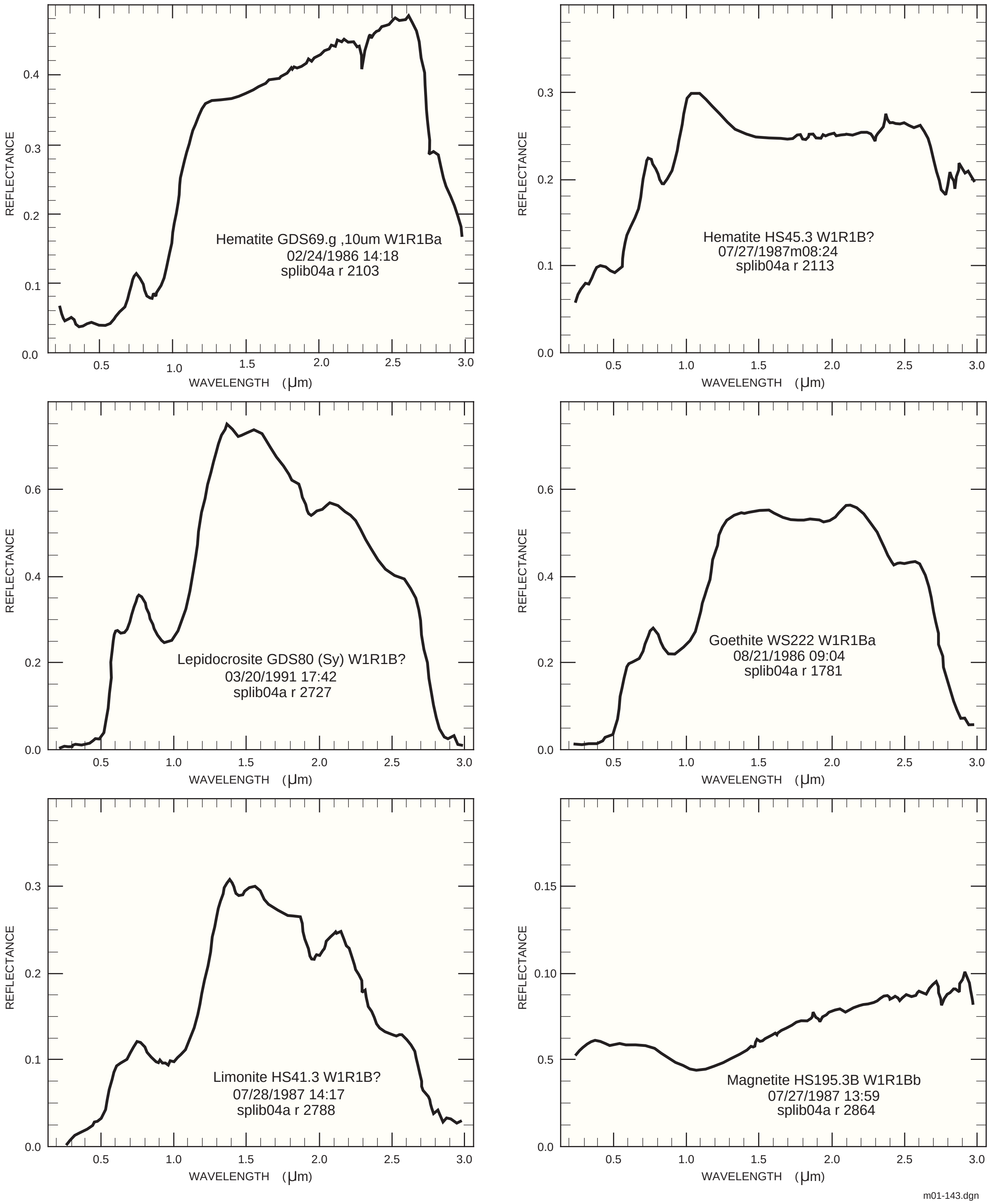

Figure 12. Spectra of iron oxide minerals, from USGS digital spectral library (after Clarke *et al* 1993)

magnets) or industrial (eg pigments). Traditionally, iron ore has been categorised as high-grade (>60% Fe), low-grade (usually 30-35% Fe), manganiferous iron ore (>2% Mn) and siliceous iron ore (>18% SiO_2). It can be further subdivided into low phosphorus (<0.07% P) and high phosphorus (>0.07% P) types.

Metallurgical and industrial uses

Metallurgical grade.

The iron and steel industry consumes some 98% of all iron ore produced. A great number of commercial alloys have iron as a constituent. These are known as ferroalloys and include iron-aluminium, iron-carbon, iron-chromium, iron-chromium-nickel, iron-chromium-aluminium, iron-cobalt, iron-manganese, iron-nickel, iron-silicon and iron-tungsten. Pig iron (also known as cast iron), wrought iron and steel are iron-carbon alloys. By changing the proportions of various elements (eg Si, Cr, Ni, W), it is possible to make iron alloys suitable for a great variety of uses (**Table 4**).

Type	Fe	C	Mn	Si	Cr	Ni	Co	W	Mo	Al	Cu
Heat-resistant alloy castings	Bal	0.3-0.5	-	1-2	8-30	0-7					
Heat-resistant cast irons	Bal	1.8-3.0	0.4-1.5	1.0-2.7	1.75-5.5	14-30					
Corrosion-resistant alloy castings	Bal	0.03-0.2	1.5 max	1.5-2.0	18-27	8-31					
Corrosion-resistant cast irons	Bal	1.2-4.0	0.3-1.5	0.5-3.0	12-35	5 max			4 max		3 max
Magnetically soft materials	Bal								3.5	16	
Permanent-magnet materials	Bal						12		20		
	Bal					17	12.5			10	6
Low-expansion alloys	53-61	0.5-2.0	0.5-2.0	0.5-2.0	4-5	33-35		1-3			
Constructional alloy steels	Bal	0.25	0.4	0.2	1.5	3.5					
	Bal	0.4	0.7	0.3	0.8	1.8			0.25		
	Bal	0.4	0.7	0.3	0.85				0.25		
	Bal	0.6	0.85	2.0	0.65						
	Bal	0.15	0.75	0.25	0.25	0.75			0.3		0.35

Table 4. Some typical composition ranges (as percentages) of iron alloys (modified from McGannon 1987). Alloys are classified according to use. Bal = balance percent of composition

Marketable ore has high iron (>64% Fe is considered export-grade) and low silica (<10%), alumina (<5%) and phosphorus (<0.08%). However, low-grade magnetite deposits can be beneficiated to produce export-grade products (eg the Savage River operation (Tasmania) mines *in situ* ore grades of 47% Fe_3O_4 or 34% Fe, but produces a concentrate grading 68% Fe). Approximate tolerance limits for minor elements in iron ore have been quoted as Cu 50 ppm, Pb 500 ppm, Zn 200 ppm, S 1000 ppm, As 50 ppm, Cr 300 ppm, Ni 300 ppm, Sn 100 ppm, V 60 ppm and TiO_2 100 ppm (Gross 1993).

Cumulative contents of minor elements in ore material supplied to the furnaces greatly influences and may determine the metallurgical processes that can be used to convert iron ore to iron and steel. The evaluation of the iron ore material involves chemical and mineralogical analyses, physical testing (eg size distribution and strength) and pilot plant trials to assess the product properties (Cripps-Clark and Pepper 1981).

Industrial grade.

A small amount (~1%) of iron ore is mined for pigments and cement manufacture. Pigmentary iron ores are selected for their special physical-chemical properties and are able to attract a premium price (up to US$1000/t) over iron ore used for steel making. Pigment types can be subdivided based on colour (**Table 5**) to yellow iron oxide, red iron oxide, brown iron oxide and black iron oxide (Podolsky and Keller 1994).

Desired chemical properties of pigment material include being relatively non-reactive, having low levels of heavy metals and toxic elements and possessing a high degree of light-fastness (Podolsky and Keller 1994). Physical requirements relate to oil absorption, surface area, particle size and shape, and magnetic and optical properties. Natural iron oxide pigments are used to give colour, body and opacity to paints and many other materials, including plaster, mortar, cement, rubber, plastics, concrete pavers, paper and roofing tiles. Specular hematite, in particular, is an important component in metal paint primers and industrial maintenance finishes as part of a corrosion control system.

Iron ore is added to Portland cement when the normally used raw materials contain insufficient iron oxides (Pratt 1978). The approximate chemical composition of Portland cement is CaO 65-66%, SiO_2 21-22%, Al_2O_3 3-8% and Fe_2O_3 3-5%. Some of these components are present in the limestone raw material, but frequently SiO_2, Al_2O_3 and Fe_2O_3 must be added separately. Al_2O_3 and Fe_2O_3 assist in the formation of calcium silicates in the clinker and lower the temperature required to produce the clinker. There are no particular grade requirements for iron oxides used in cement production, but proximity to the cement plant is important (Pratt 1978).

Magnetite can be used as dense medium in mineral separation processes due to its high density (SG = 5) and magnetic properties. In mineral dressing, a dense medium is used to separate mineral species with different specific gravities. Dense medium baths or cyclones are commonly part of coal washing plants that remove silicate rock fragments from the coal. Magnetite is preferred because it is low cost, easily handled and can be effectively recovered by magnetic separators (Pratt 1978). Size specifications for magnetite used in dense medium baths and cyclones are 95% < 105 µm and 93-97% < 53 µm, respectively (Pratt 1978).

Ore extraction and treatment – a summary

Mining of iron ore is generally carried out by large operations using surface methods that extract 0.5-30 Mt pa. Underground mining of iron ore is still conducted in a few large, well established deposits in Sweden (eg Kiruna Mine). There are currently no iron ore operations in the NT, but a number of iron ore mining operations in Australia are documented in Woodcock and Hamilton (1993). Any future mining operations in the NT would essentially be small-scale (eg at Frances Creek) to medium-scale (eg at Roper River). The size of operations at Roper River would probably be

Table 5. Classification and examples of pigment iron ores (modified from Podolsky and Keller 1994)

	Yellow iron oxide	Red iron oxide	Brown iron oxide	Black iron oxide
Natural minerals	Goethite, limonite, lepidocrocite, ochres, siennas	Hematite, siderite (calcined)	Umbers, goethite, limonite (calcined)	Magnetite, maghemite
Ore source (example)	France	Spain	Cyprus	USA
Fe_2O_3 %	20	85	45	98
MnO_2 %	Trace	Trace	11	Trace
SiO_2 %	50	6.5	25	1.5
Particle size range (µm)	0.2-40	0.25-15	0.6-7	1-10
Median size (µm)	4.0	1.5	3.0	-
Oil absorption	32	17	44	15

similar to that at the Jimblebar iron ore mine in Western Australia.

The Jimblebar iron ore mine is a medium size (5 Mt/yr) operation based 42 km east of Newman in the Hamersley Iron province (see Pearson and McGregor 1993). Jimblebar produces lump ore @ 65% Fe and fines @ 62% Fe products from enriched martite-goethite BIF material in the Joffre Member of the Brockman Iron Formation. The low phosphorus content (0.03%) makes Jimblebar ore ideal to blend with the higher phosphorus ore from BHP Billiton's Mount Newman operations. The 51 Mt @ 63% Fe deposit was drilled out on a 25 m x 25 m pattern. Mapping the three dimensional boundaries of eleven distinct units of ore and waste were the basis of a computerised block model of the deposit. This model contained 5 m^3 blocks with Fe, P, Al_2O_3, SiO_2 and LOI values, together with SG and ore type. Hydraulic excavators and 85 t capacity rear dump trucks remove and haul the ore material to the crusher stockpiles, where it is blended into the crusher to achieve the grade required.

During the treatment process, high-grade iron ore is usually crushed and screened to provide direct lump feed (6-30 mm in size) and sometimes fines feed (>6 mm in size) direct to blast furnaces and smelters. The fines can be processed to produce either high-grade sinter (agglomerated fines) or pellets. Low-grade ore (eg magnetite BIFs, some Fe skarns, proximal hydrothermal and oolitic deposits) is usually beneficiated and upgraded by gravity, magnetic separation, and/or floatation of the ore minerals, followed by sintering or pelletising (agglomeration processes). Most of the iron ore mined in the USA is derived from magnetite-BIF that is upgraded from 25-35% Fe head grade to 64% Fe in pellet products.

The following descriptions of iron and steel making processes is largely derived from St Pierre (1987), Labson *et al* (1994) and information obtained from the America Iron and Steel Institute website (URL: http://www.steel.org/learning/).

The conversion of iron oxide to metallic iron is accomplished by the application of heat and reducing agents. The reducing agents CO and H_2 are derived from coal, natural gas or oil.

$$Fe_2O_3 + 3CO + \text{heat} \rightarrow 2Fe + 3CO_2 \qquad \sim 1200^{\circ}C \qquad (1)$$
$$Fe_2O_3 + 3H_2 + \text{heat} \rightarrow 2Fe + 3H_2O \qquad (2)$$

In most steelworks, this first stage would take place in a blast furnace (**Figure 13**) where iron ore (as lump, pellets or sinter), fluxes (limestone) and coke or pulverised coal are the inputs. Preheated air that often contains hydrocarbons (gas or oil) is blasted through the base of the cylindrically shaped furnace. Limestone is melted to become the slag that removes sulfur and other impurities. The molten iron is then combined with fluxes and scrap steel (if available) and smelted in a basic oxygen, open hearth or electric arc furnace to produce molten steel. This is then transferred to the ladle furnace where alloys are added to produce the required quality of steel.

In the direct reduction of iron (DRI) method (**Figure 13**), iron ore is fed into a furnace as high-grade (>67% Fe) lumps, fines or pellets and heated with natural gas (eg Midrex process). A solid (pellet or briquette) metal product containing about 90% Fe is produced that can be used in electric arc and basic oxygen furnaces as a substitute for scrap iron. DRI is not a substitute for molten iron produced via blast furnaces because of the significant amount of impurities (residuals) that remain in the product. Direct reduction plants are often located in areas where there are abundant supplies of inexpensive natural gas and where the price of scrap metal is relatively high.

Direct smelting (DS) is relatively new technology that produces molten metal from iron ore using pulverised coal as an inexpensive fuel and reductant. The molten metal produced can be used without further processing as a feedstock for electric arc or basic oxygen furnaces (**Figure 13**). Relative to blast furnaces, DS has advantages in raw materials savings, in being smaller in scale and in having lower capital costs, greater production flexibility and fewer environmental problems. DS also has an advantage over DRI in that iron ore specifications are less demanding. Examples of direct smelting technology include the COREX, AISI Direct, HIsmelt, ROMELT and DIOS processes that are described in detail by Feinman (1999).

IRON ORE DEPOSITS OF THE NT

Iron ore exploration and mining in the NT

The first significant iron ore find in the NT was made in 1911 at Murphy's prospect near Roper Bar (Murphy 1912). This small discovery drew BHP Ltd to the area in 1955 and led to an investigation of the Roper River oolitic iron ore deposits. Diamond drilling, bulk sampling and some metallurgical testing of deposits near Hodgson Downs (Deposits T, U, V and W) Mount Fisher (Deposit M) and Sherwin Creek (Deposits A, B, C and E) was carried out between 1956 and 1961. Canavan (1965) estimated iron ore resources of 200 Mt grading 27-33% Fe and 40-45% SiO_2 at

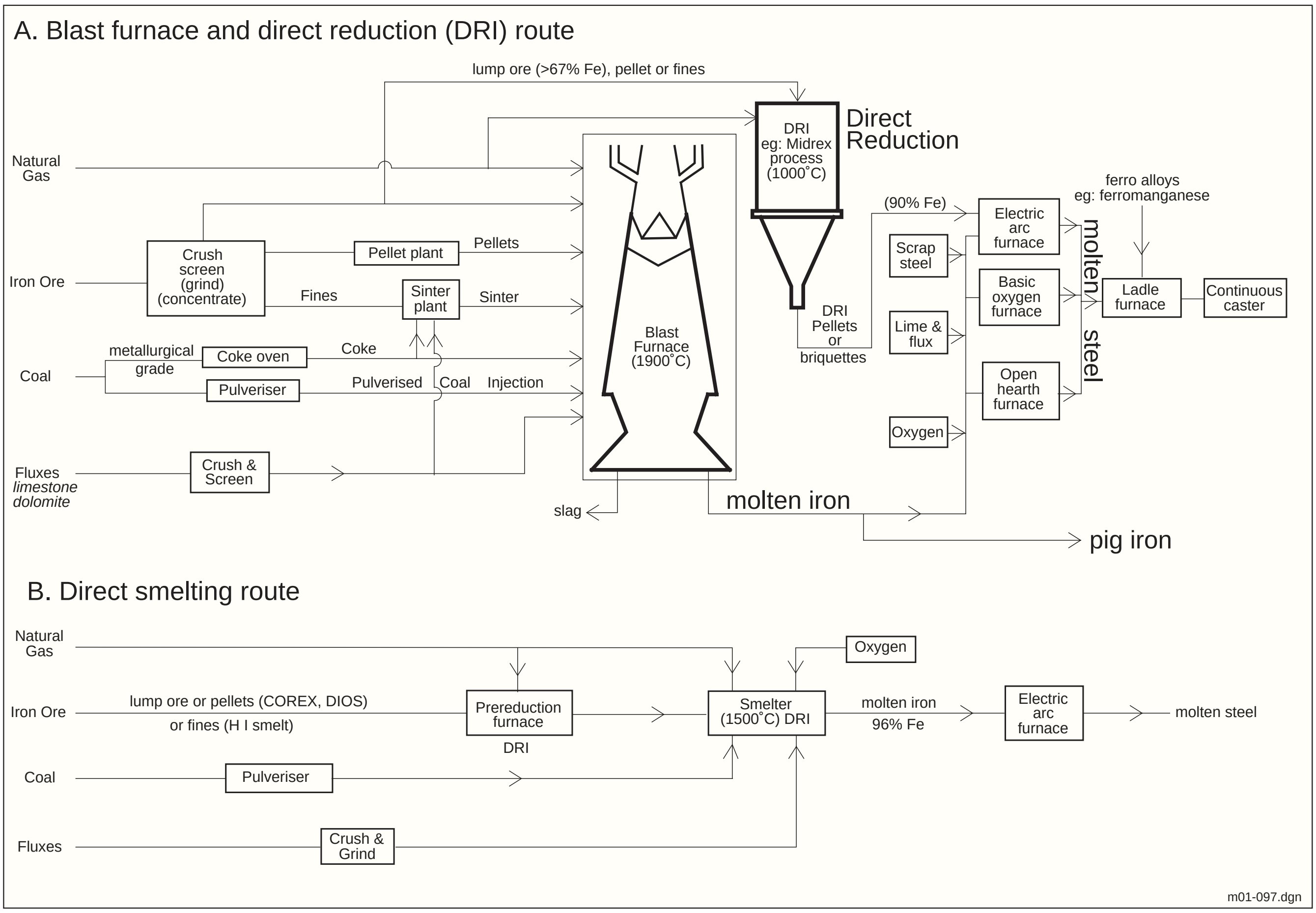

Figure 13. Flowchart showing blast furnace and direct smelting ironmaking processes (modified from Labson *et al* 1994)

Sherwin Creek, and 200 Mt grading 37-52% Fe and 7-16% SiO_2 at Hodgson Downs. The Roper River deposits were not developed due to their inferior quality and small size relative to the Pilbara iron ore deposits that were discovered between 1957 and 1962.

Regional mapping by the BMR in 1956 over the *Mount Bundey* area to the southeast of Darwin identified a prominent ironstone outcrop, although a diamond drillhole by the BMR in 1958 failed to intersect the lode after 152 m of drilling. Further diamond drilling in 1962 by the Northern Territory Mines Branch and in 1964 by the BMR established an ore resource of 1.5 Mt grading 64% Fe, 0.05% P and 0.07% S (Dunn 1964). The magnetite-rich deposit was mined between 1968 and 1971 by Morgan Mining Ltd and produced 843 063 t of ore grading 63.4% Fe, 0.057% P and 0.11% S (Ryan 1975). Mining operations ceased when the level of sulfur in the ore exceeded market specifications.

In 1961, prospector L Harmanis located an aboriginal ochre “mine” within massive hematite lenses at Ochre Hill, north of Pine Creek. Early exploration (1962-63) initially concentrated on the discovery site at Ochre Hill, then moved to higher-grade iron ore lenses in the southern part of the *Frances Creek iron field*. A pre-mining resource of 5.14 Mt grading 64% Fe was estimated for the southern part of the field (Elliot 1965).

Mining of the southern deposits was undertaken by Frances Creek Iron Mining Corp. Pty Ltd (FIMCO) between 1966-74 and some 7.98 Mt of ore grading 59% Fe was produced (Bagas 1981). Most of the iron ore was obtained from the Helene 6/7 pit. Other pits included Thelma 1 and 2, Rosemary, Jasmine West, Jasmine Central, Helene 10, 9, 8, 5, 4, 3 and 2. Mining operations were drastically reduced during 1973 when the Japanese ore market cut back on their original purchase estimates. Subsequently in July 1974, the North Australian Railway increased freight charges by 50% and effectively put FIMCO out of business (Barrie 1999).

The establishment of two iron ore mining operations in the Darwin-Pine Creek area during the 1960s encouraged iron ore exploration throughout the Pine Creek Orogen (PCO). Hydrothermal Fe occurrences to the east of Frances Creek were discovered and investigated by Wandaroo Mining Corp (Ward 1970). Several other distal hydrothermal and surficial occurrences (eg *Rum Jungle*, *Beestons*, *Howley* and *Daly River Road*) have been assessed and small subeconomic iron ore resources have been examined by various mining companies (Murphy 1968, Pritchard 1969, Sullivan 1970, Burban and Svenson 1970).

The discovery and development of large, high-grade iron ore deposits in the Pilbara region in Western Australia has resulted in only minor exploration for iron ore being undertaken across the NT since 1974. Government regional geological mapping and company gold exploration work has identified several ironstones in the Reynolds Range area in the northern Arunta province. At the abandoned Mount Bundey mine, potential tonnages of near surface iron ore material were assessed using ground magnetics data, ore dump samples and shallow percussion drillholes (Orridge 1993c). Additional sampling has also been carried out on some of the Roper River iron ore deposits (Orridge 1993a, Ferenczi 1997a).

Production of iron ore in the NT (**Figure 14**) is essentially confined to a nine year period between 1966 and 1974 and this coincides with the Frances Creek operation. Total iron ore mined in the NT over this period was 9.3 Mt and this yielded some 6.8 Mt of iron ore product grading 62% Fe for 4.2 Mt of metallic iron. Existing iron ore resources are relatively small; Roper River deposits may contain 200-400 Mt of low-grade material and the Frances Creek iron field and Tennant Creek tailings contain about 1.5 Mt and 16 Mt of marginal iron ore, respectively. A tabulation of iron ore occurrences with geological details is presented in **Appendix 1**.

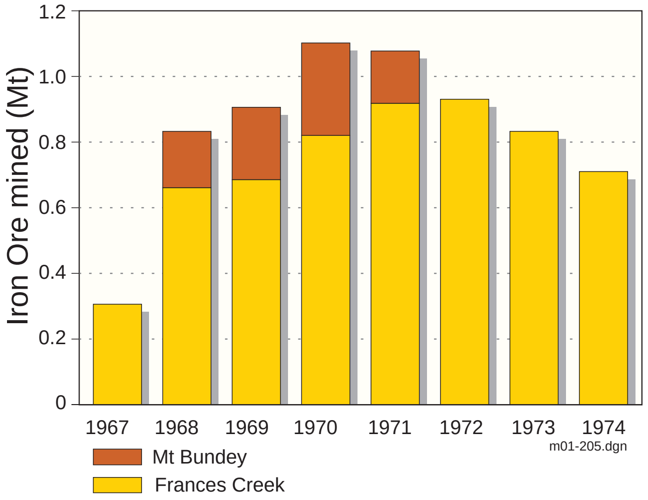

Figure 14. Past production of iron ore in Northern Territory

Classification and distribution of iron ore deposits of the Northern Territory

For the purposes of this publication, the iron ore deposits of the Northern Territory are divided into four different types: oolitic sedimentary deposits (eg Roper River deposits); distal hydrothermal deposits (eg Frances Creek and Tennant Creek ironstones); skarn deposits (eg Mount Bundey); and surficial deposits (eg Daly River Road and Howley prospects). These deposit types are briefly described below and discussed in more detail in the following sections.

Oolitic sedimentary deposits

These are massive stratiform oolitic ironstones within marine terrigenous clastic sediments. Kimberley (1978) has called them sandy, clayey, and oolitic, shallow-inland-sea iron formations or SCOS-IFs, but they are also known as Clinton-type oolitic ironstones. The ironstones are interbedded with shale and quartz sandstone, which were deposited in an agitated, shallow marine depositional environment. The main iron minerals present are goethite, hematite, limonite, siderite, chamosite, greenalite and traces of magnetite. Gangue minerals include detrital quartz and authigenic chert.

Mesoproterozoic iron ore deposits in the Roper River district are examples of this style of iron mineralisation in the NT. Oolitic ironstones form beds 0.5-4 m thick that are commonly continuous over tens of kilometres. Ore quality is generally low, typically 30-50% Fe (av 40%), 0.2 to 0.05% P (av 0.1%) and 15-45% SiO_2 (av 30%) although better quality ore (>50% Fe, <30% SiO_2 and 0.1% P) exists in some areas (eg Deposit W). Oolitic ironstones are also present in the South Nicholson, Amadeus and Georgina basins.

Hydrothermal deposits

Proximal and distal hydrothermal iron ore deposit styles are both present in the NT. Proximal deposits include essentially low tonnage and low-grade vein deposits in the Arunta province (eg Patty Well). In the southern part of NAPPERBY, some 35 quartz-hematite veins occupying west-trending faults in Proterozoic granites have been reported along Stuart Bluff Range (Clarke 1968). Three unnamed vein-hosted occurrences are known in the central area of HUCKITTA. These minor hydrothermal occurrences have some potential to host significant gold mineralisation and are not described in this publication.

Distal hydrothermal deposits are massive stratabound ironstone lenses hosted in Palaeoproterozoic, ferruginous marine clastic lutites. These rocks acted as the protore from which the iron has been mobilised into nearby geological structures. Hydrothermal fluids derived from magmatic or connate brines during orogenic activity have remobilised sedimentary iron in the host sequence into adjacent stratigraphic and structural trap sites. In the Tennant Creek Mineral field the ironstones are hosted in the Warramunga Formation and consist of pipe-like to podiform lenses containing magnetite and minor quartz, chlorite, muscovite and sulfides. In the Frances Creek iron field the ironstones are hosted in the Wildman Siltstone and consist of tabular lenses containing platy hematite and minor quartz. Ironstone lenses in the Rum Jungle (Pine Creek Orogen) and Harverson Pass (Arunta province) areas are also examples of this style of mineralisation.

Skarn deposits

This classification is applied to rocks with significant proportions of iron introduced by igneous and metasomatic processes. Ironstones in the Mount Bundey area are the best examples of this deposit type. The tabular lenses are composed of magnetite with minor sulfides below the zone of oxidation. Argillaceous lithologies of the Wildman Siltstone and syenite (Mount Goyder Syenite) host the mineralisation, which was probably derived from the intrusion of the voluminous Mount Bundey Granite.

Surficial deposits

These deposits are widely distributed across the Northern Territory and have formed by surface and near surface iron enrichment processes. The ore does not persist below the zone of weathering. Some small deposits are related to Cretaceous unconformities (eg at Daly River Road and Tawallah Range) and ferruginous parent rocks (eg Elcho Island and Howley prospects). Goethite, limonite and fine earthy hematite are the dominant ore minerals. High levels of impurities coupled with low ore grades and tonnages often characterise this style of mineralisation.

Oolitic sedimentary (Clinton-type) deposits

Some 27 oolitic ironstone occurrences have been recorded in the Northern Territory. Most of these are within the Sherwin Formation in the Roper River iron field. The Roper River

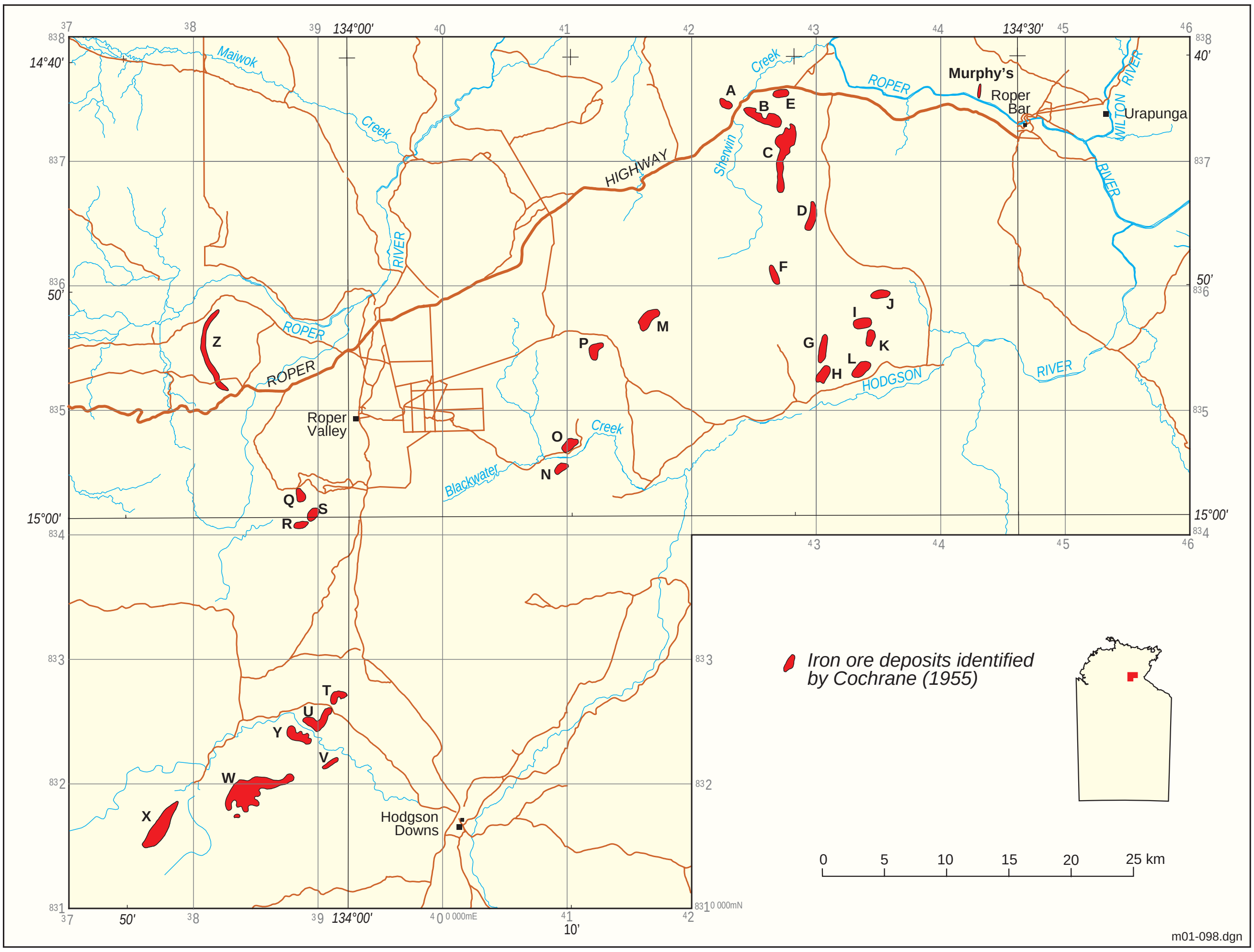

Figure 15. Location of iron ore deposits in Roper River region

deposits were investigated between 1956 and 1961 and are relatively well known. Occurrences of equivalent age occur in the South Nicholson Basin, but very limited information on them is available. A few thinner oolitic ironstones (eg at *Kipper Creek*) have been recorded in the lower parts of the Roper Group (1430-1490 Ma) succession. Minor occurrences of Ordovician age in the Amadeus and Georgina Basins are briefly described.

McArthur Basin

Roper River iron field

The Roper River iron field is located about 120 km east of Mataranka, between the Roper and Hodgson Downs Rivers (**Figure 15**). Iron ore was first reported in the area at Murphy's prospect during a regional prospecting survey in 1911 (Murphy 1912). Between 1955 and 1961, BHP Ltd investigated some 27 iron ore prospects (deposits A to Z and Mount Karmain) to the west and southwest of Murphy's prospect. This work included geological mapping, drilling (38 diamond drillholes totalling 1793 m), shaft sinking, sampling and metallurgical testing of composite samples (Cochrane 1955, Bennett and Heaton 1958, Salamy 1958, Vivian 1962). Samples from cliff exposures and test shafts were submitted to the CSIRO for petrological examination; results of this work were presented in a number of unpublished reports (Baker and Edwards 1956, Edwards 1956a, b 1957a, b) and in a published report by Cochrane and Edwards (1960). At about the same time, Carpentaria Exploration Ltd conducted a program of geological mapping, rock chip sampling and drilling at the Kipper Creek iron prospect (Williams 1962). More recent exploration work has been carried out on some of the iron ore deposits (Orridge 1993a) and in the mid 1990s, the NTGS conducted a geological investigation and review of the Roper region iron ore deposits (Ferenczi 1997a).

The Roper River iron field lies within the southwestern part of the McArthur Basin (**Figure 9**), in URAPUNGA and HODGSON DOWNS. Quartz sandstone and interbedded micaceous mudstone and shale dominate the geology. These rocks are assigned to the Mesoproterozoic Roper Group and they form long cuesta-form ridges and broad flat-floored valleys, respectively. The gently dipping shallow marine cyclic sandstone and mudstone succession is up to 2000 m thick and was intruded by tholeiitic dolerite sills prior to regional deformation. Illite from the Kyalla Formation has been dated by Rb-Sr method at 1429 ± 31 Ma (Kralik 1982). Iron ore occurrences are present at several stratigraphic levels within sediments of the Roper Group, but the main exploration targets to date have been the Sherwin Formation and the Wadjeli

Figure 16. Bench forming massive oolitic ironstone bed exposed along southern part of Deposit W

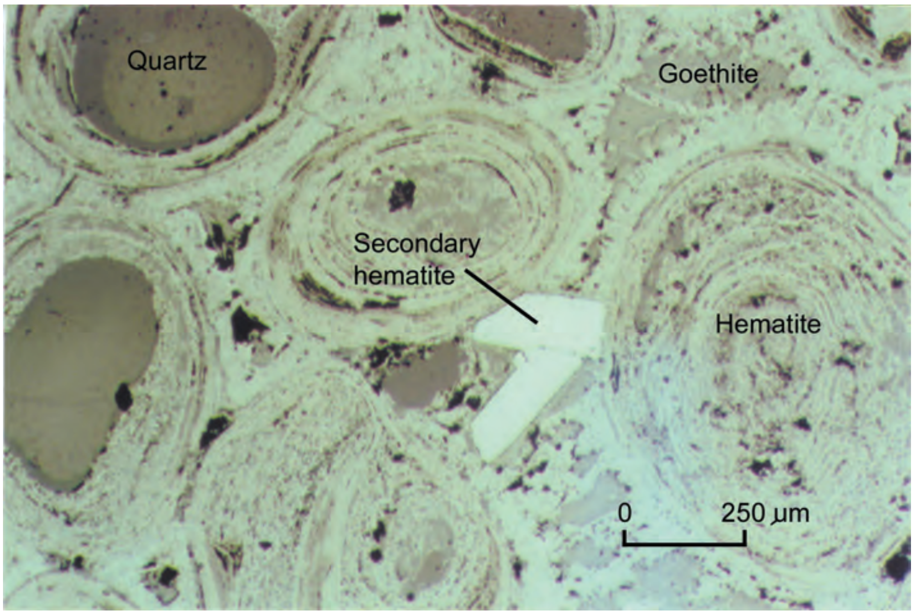

Figure 17. Hematite-goethite ooliths and secondary hematite laths from Mount Fisher deposit (NTGS R035, reflected light)

Sandstone Member within the Mainoru Formation (Kipper Creek prospect).

The Sherwin Formation contains massive oolitic to pisolitic ironstone within interbedded medium to very coarse ferruginous (chamosite-siderite at depth) ripple-marked sandstone, sandy mudstone and shale. Massive ironstone beds are typically 1-4 m thick and are often exposed near the tops of cliff faces at the front of long cuesta-form ranges (**Figure 16**). Within the Sherwin Formation, a soft, ochreous oolitic ironstone bed near the base has better economic potential than the harder upper ironstone beds as it is higher in iron and contains less silica. This bed is best exposed along a ridge about 12 km to the west-northwest of Hodgson Downs homestead (Deposits W, V, Y, U and T) and at Mount Fisher. The ore typically consists of closely packed ooids (0.5-5 mm in diameter) of soft red hematite and goethite, and varying amounts of well rounded quartz grains (**Figure 17**). Below a depth of 20 m, the ore consists predominantly of hematite and greenalite[1] ooids within a hematitic cement (Cochrane and Edwards 1960). Silica grains commonly form the nuclei of the hematite ooids.

The 'upper' ironstone beds have been well documented in the Sherwin Creek area where a number of drillholes have intersected three 'upper' ironstone horizons (**Figure 18**). These ironstones are lower in iron than the 'Main Ironstone' interval as they contain more siderite and quartz and less hematite in the primary ore. The 'upper' ironstones are interbedded with coarse siderite-chamosite-bearing sandstone and sandy mudstone. Sedimentary features within the Sherwin Formation (Ferenczi 1997a) suggest that it was deposited as an offshore bar in an active shoal environment (**Figure 21**) that transgressed over lagoonal mud and beach sand (Moroak Sandstone). Inner shelf, organic-rich mud (Kyalla Formation) subsequently transgressed over the ferruginous oolite beds.

Several hundred million tonnes of ironstone rock is present in the Roper River area. Previous resource estimates

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[1] $Fe_6Si_4O_{10}(OH)_8$ - a variety of chamosite.

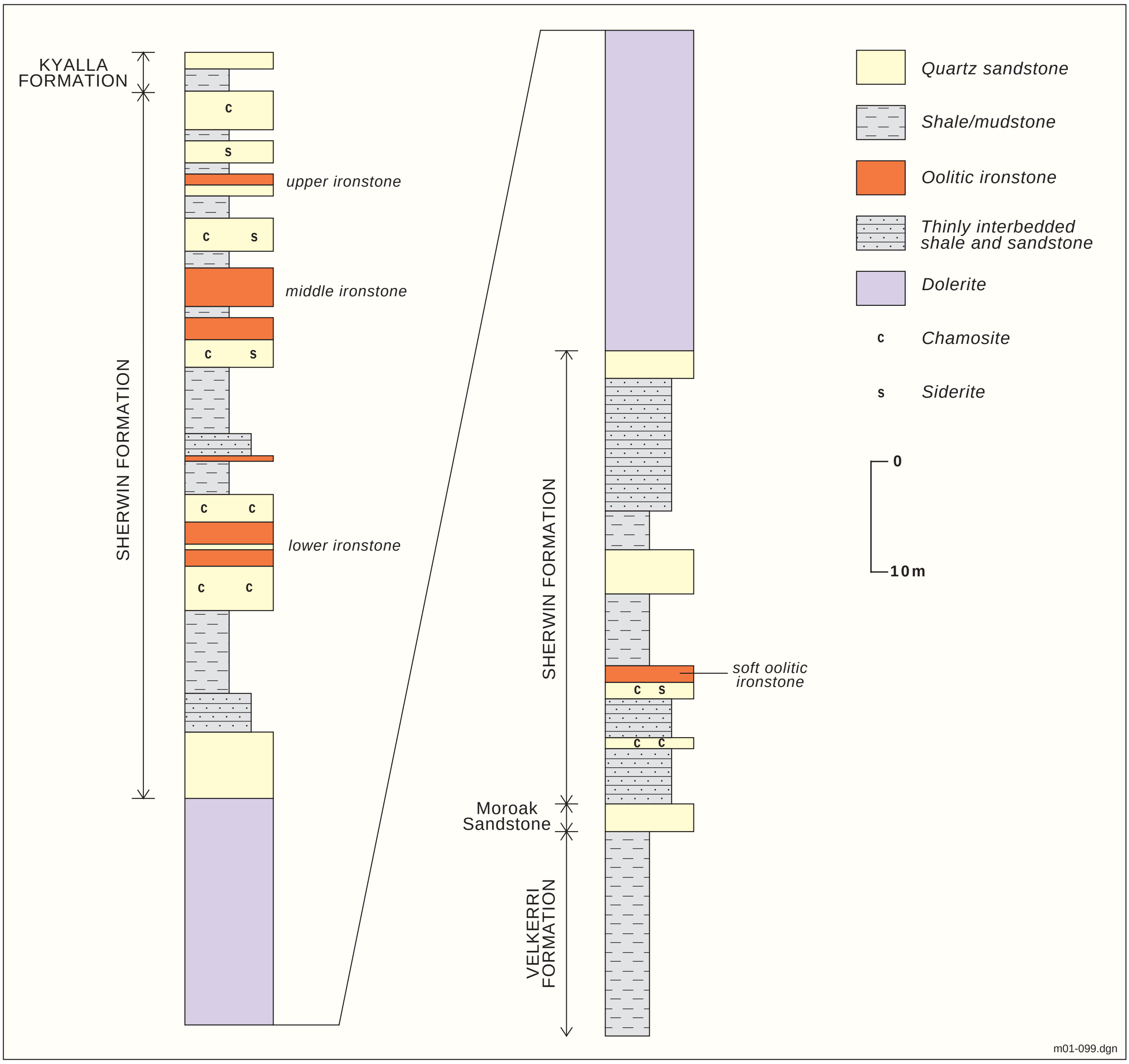

Figure 18. Stratigraphic section from Sherwin Creek area (based on drillholes BHP DDHB7 and BMR URAPUNGA DDH4)

(Cochrane 1955, Canavan 1965 and Orridge 1993a) were based on data that was insufficient to allow the geological framework to be confidently interpreted and the continuity of the ore to be predicted. These estimates could therefore be classified as an inferred resource according to the Australasian code for reporting of mineral resources and ore reserves (JORC 1999). The southern area (Deposit W) of the Hodgson Downs deposits is the most promising and contains an inferred resource of 60 Mt grading 50-55% Fe (Orridge 1993a). In the Sherwin Creek area, Cochrane (1955) estimated a subeconomic inferred resource of 183 Mt grading 40.8% Fe at Deposit C and 37.4 Mt grading 36.3% Fe at Deposit B. Mount Fisher has a potential resource of 4 Mt grading 45-50% Fe.

The Hodgson Downs deposits (T, U, V, W, and Y) lie within mining reserves RO 1377 and 1378 on land belonging to the Alawa Aboriginal Land Trust. In this area, the Sherwin Formation forms a distinctive mappable unit up to 8 m thick that can be discontinuously traced for some 25 km around the southern and eastern margin of a shallow northeast-plunging syncline. The unit appears to vary in both thickness and composition from north to south, and the dip progressively decreases from 22° in the north to near horizontal in the south. Most of the drilling and sampling has focused on the gently dipping and thicker ironstone sections exposed around the southern part of Deposit W (**Figure 19**). A schematic cross-section based on drillholes by BHP Ltd is given in **Figure 20**.

The sub-horizontal ironstone unit at *Deposit W* averages 40-50% Fe over 4-4.5 m, and includes an upper 2.5-3.5 m section of massive, soft oolitic ironstone, which grades 43-63% Fe. The best drillhole intersection (BHP DDH W26) was 4.5 m grading 42.9% Fe and 12.5% SiO_2 from 18.7 m depth (Bennett and Heaton 1958). Surface sampling by Ferenczi (1997a) indicated the presence of moderate to high amounts of phosphorus (0.06–0.18% P, av 0.12%) and silica (7.4–33.4% SiO_2, av 22%). Steeper dipping (10-22°) ironstones in the northern part of Hodgson Downs (*Deposits T, U, V and Y*)

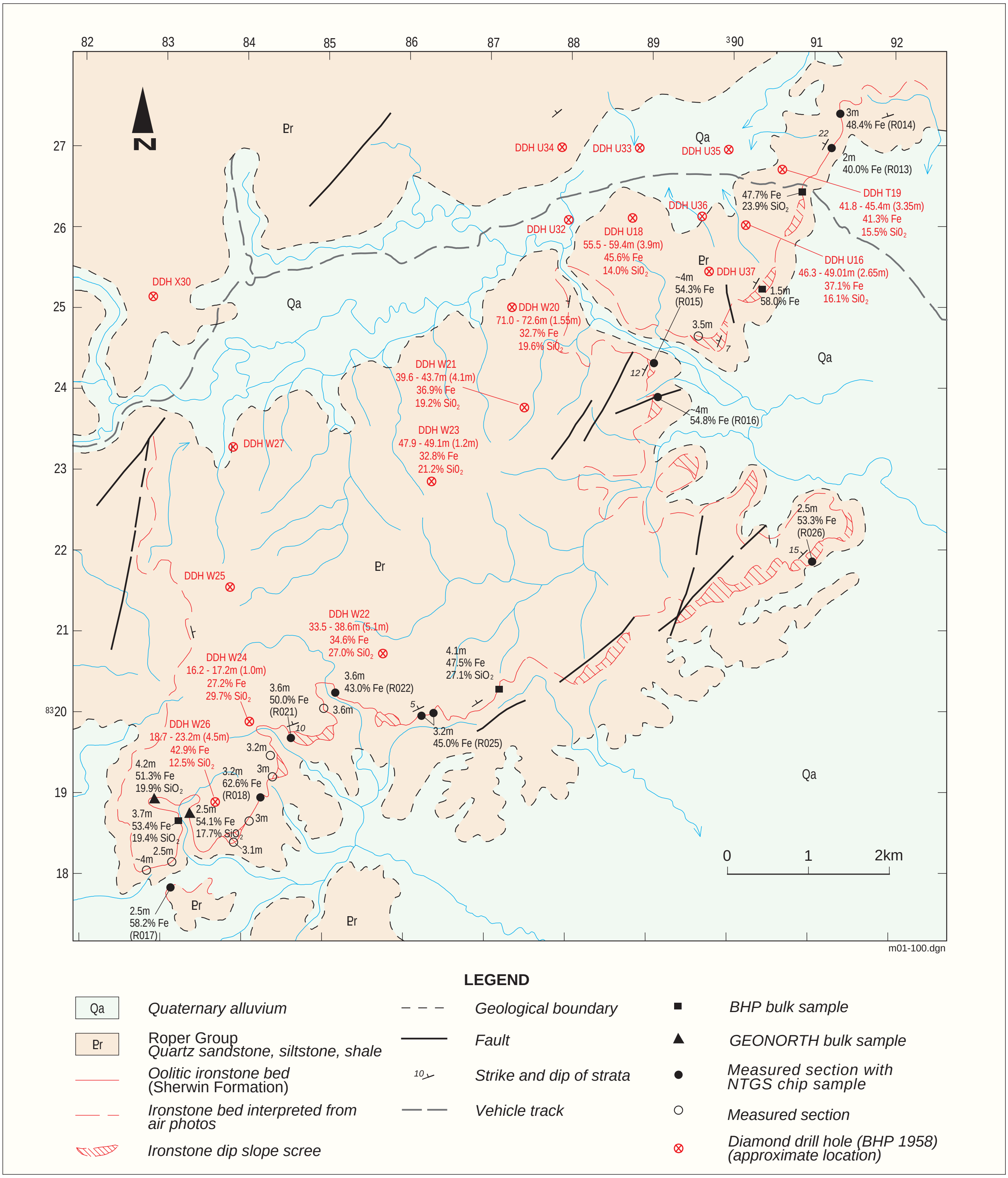

Figure 19. Simplified geological map of Hodgson Downs iron ore deposits

are generally thinner and lower in grade than the ironstones at Deposit W. Assays from drillhole intersections of the main ironstone bed averaged 42% Fe over 2.6 m (Vivian 1962), whereas surface sampling returned 37-48% Fe from 2.7-4.1 m sections.

The Sherwin Creek deposits (A, B, C, D, and E) lie within mining reserve RO 1373 on the Mt McMinn pastoral lease. Four distinct ironstone beds were identified and sampled over this area by BHP Ltd (Cochrane 1955, Bennett and Heaton 1958, Cochrane and Edwards 1960). The upper three ironstone units (upper, middle and lower beds) are low-grade (average 38% Fe) ferruginous oolitic sandstones with high silica (average 42% SiO_2). These ironstone units comprise the iron ore resources for Deposits A, B and C. The lowest ironstone unit lies below a dolerite sill and was referred to as the No 4 unit by Canavan (1965). This ironstone is exposed

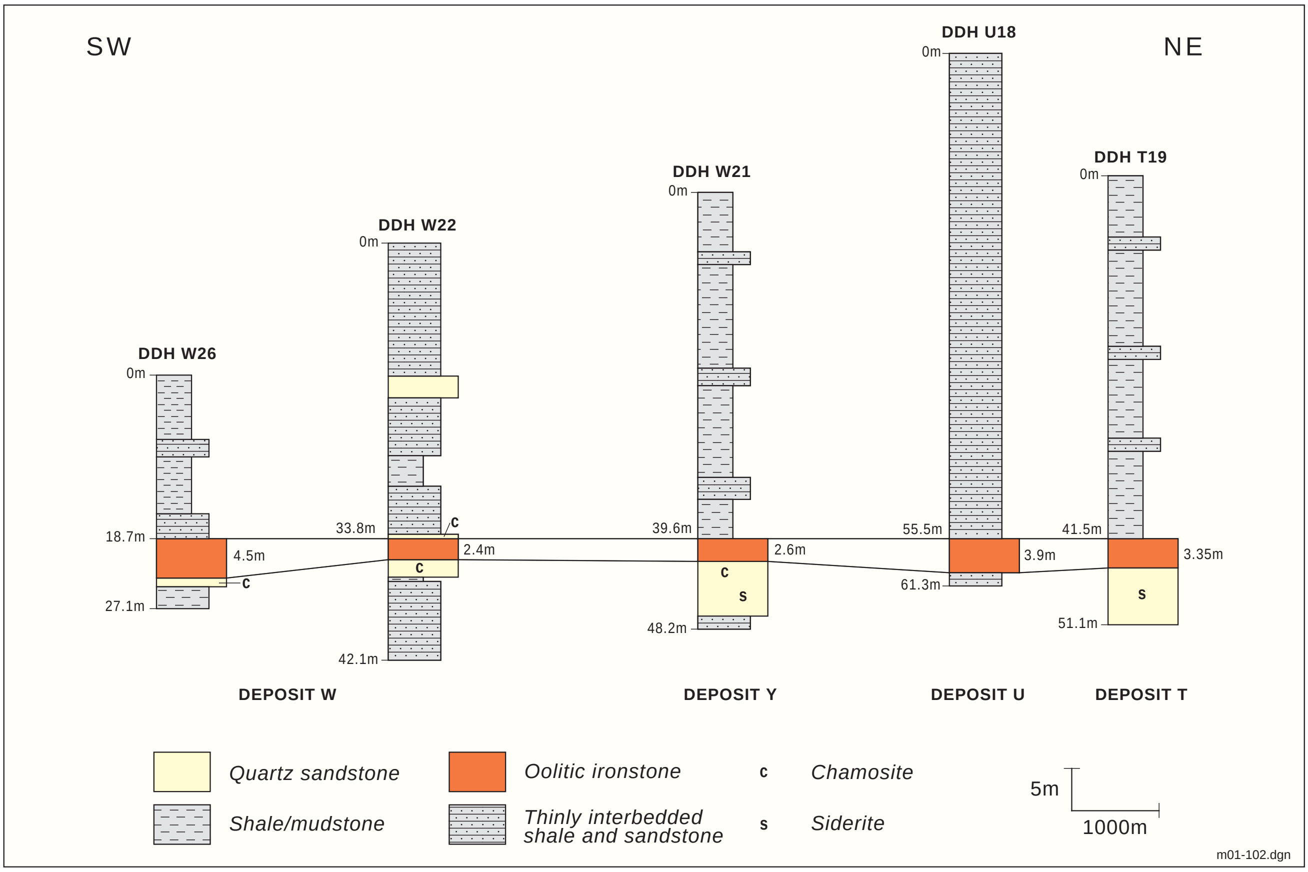

Figure 20. Drillhole intersections of hematite-rich oolitic ironstone, Hodgson Downs

at Deposits D and E. It is much softer, higher in grade (45-52% Fe) and composed of predominately oolitic hematite. The upper bed is typically 1-3.5 m thick and is low in iron (only 30-35% Fe) compared to the lower units. The middle ironstone bed is separated from the top bed by about 4.5 m of interbedded shale and sideritic sandstone. Sampling and drilling intersections indicate that the middle bed is 3.5-12 m thick (it often includes interbedded shale beds up to 1.2 m thick) and has relatively low grades (33-43% Fe). Cochrane (1955) estimated an inferred resource of 90 Mt grading 38.1% Fe for the middle bed at *Deposit C*. Surface sampling of the lower ironstone bed by BHP Ltd along the eastern side of Deposit C indicates that the unit averages 7.3 m in thickness and grades about 45.5% Fe and 28.5% SiO_2 (Cochrane 1955).

At *Deposit E*, the exposed ‘Main Ironstone’ bed forms a rubbly veneer (0.5-1 m thick) on a gentle dip slope along the top of the western half of the ridge and a 2 m cliff in the eastern part. A channel sample collected from a 1.7 m thick ironstone section at AMG 429630 mE 8375460 mN averaged 48.0% Fe, 22.8% SiO_2 and 0.20% P. The material consisted of soft, oolitic to pisolitic (1–3 mm) hematite-rich ironstone and minor sand towards the base.

At *Mount Fisher* (Deposit M), the main ironstone bed is exposed around the western and northern section of an escarpment which dips gently (5-10^o) to the southeast. The ironstone is up to 4 m thick and assays 45-60% Fe, 20-26% SiO_2 and 0.17-0.23% P. Drillhole DDH M17 intersected a 3.7 m section of the main ironstone which returned 47.2% Fe and 26.3% SiO_2 from a depth of 22.3 m (Bennett and Heaton 1958). Drillholes to the east indicate a lensing out of the ironstone unit.

Ironstone deposits G, H, I, J, K and L are exposed in the vicinity of Mount Scott (AMG 332830 mE 8352960 mN). Despite the large potential tonnage (>100 Mt), these deposits are unlikely to become economical in the foreseeable future. The ironstone consists of hard, cross-bedded, oolitic ferruginous sandstone that is similar to the upper and middle beds at Sherwin Creek. At *Deposit G*, a bulk sample (BS 2) collected by BHP Ltd assayed 57.71% Fe, 10.18% SiO_2 and 0.015% P (Baker and Edwards 1956). Orridge (1993a) collected a bulk sample from Deposit I that returned 50.4% Fe, 23.8% SiO_2 and 0.05% P over 4.5 m. At *Deposit K*, a bulk sample (BS 3) assayed 53.12% Fe, 18.52% SiO_2 and 0.046% P (Baker and Edwards 1956).

A thin oolitic ironstone horizon has been identified at the base of the Wadjeli Sandstone Member in the vicinity of *Kipper Creek* (AMG 454030 mE 8380560 mN). It extends to the east, almost continuously, for some 75 km. Carpentaria Exploration Ltd conducted regional geological mapping, rock chip sampling (116 samples) and some shallow diamond drilling in the vicinity of Kipper Creek (Williams 1962). Drilling defined an ironstone horizon up to 3.7 m thick (averaging 2.6 m) with an average grade of 29.2% Fe over a 10 km strike length. The ironstone horizon consists of two oolitic ironstone beds separated by a thin (1 m thick) ferruginous shale bed. The upper ironstone is oolitic to pisolitic in nature and averages about 1 m in thickness. It assays 31.0% Fe and 32% SiO_2 over the drilled area. The lower ironstone is oolitic, averages 0.8 m in thickness and assays 40.4% Fe and 30% SiO_2. Mineralogical descriptions of the ironstones indicate a very similar composition and texture to the Sherwin Formation oolitic ironstones (Williams 1962).

Mount Karmain prospect (AMG 357130mE 8410660mN) is located about 35 km to the south-southwest of Mountain Valley homestead and is also within the Sherwin Formation. A single drillhole by BHP Ltd (DDH MK 32) intersected a thin (0.35 m thick) pyritic, chamosite-siderite oolitic ironstone at a depth of 37.3 m (Hopkins 1959). This intersection assayed 35.8% Fe, 13.3% SiO_2 and 0.61% S. Iron grades in surface material varied from 31–40% Fe.

BMR Urapunga DDH 5, which is located about 5 km to the east-southeast of Mount McMinn, intersected two ironstone intervals within the Munyi Member of the Abner Sandstone (Sweet and Jackson 1986). The upper oolitic ironstone bed, which was intersected at a depth of 25.7 m, is about 1.1 m thick, but this includes a 10 cm siltstone interbed. The lower massive ironstone is located at the base of the Munyi Member and is about 1 m thick (33.5-34.5 m depth).

South Nicholson Basin

Second Edition geological mapping in the Carrara Range region has identified ironstones in the Mullera Formation of the South Nicholson Group. Several ironstone beds, up to 20 m thick, are exposed near the base of the formation along the southern limb of an anticline at AMG 765130 mE 7948170 mN (Sweet 1984). These oolitic ironstones contain hematite and goethite, and grade westward into ferruginous sandstone. They are equivalent to similar beds within the Train Range Ironstone Member in the Constance Ranges area in Queensland, where the oolitic ironstone beds contain about 360 Mt of medium-grade (51% Fe) iron ore (Harms 1965). The ironstone beds are also the stratigraphic equivalent of the Sherwin Formation in the Roper River iron field.

Amadeus basin

Oolitic ironstone beds of Early Ordovician age have been reported from the upper Horn Valley Siltstone (Ranford *et al* 1965, Forman 1966) and upper Pacoota Sandstone (Gorter 1991). The ironstone beds are relatively thin and reach a maximum of 1.3 m in Tent Hill 1 Well. They therefore have very limited economic potential.

Georgina Basin

Thin oolitic ironstone beds of Early to Middle Ordovician age are present in the lower Nora Formation along the southwestern limb of the Dulcie Syncline (Vine 1959). Oolitic ironstone and ferruginous sandstone beds have been identified over a strike length of 35 km between Mt Ultim and Point Spring (Vine 1959, Smith 1964). A measured section in the vicinity of Point Spring recorded oolitic ironstone beds, 0.6 m and 0.3 m thick, that are interbedded with mudstone and coarse ferruginous sandstone. A chip sample (Ha284A) from a ferruginous sandstone bed assayed 39.6% Fe_2O_3 (Smith 1964).

Ore Genesis

Oolitic ironstone beds within the Sherwin Formation are of the SCOS-IF type (Kimberley 1978, 1989a). Sandy, clayey, and oolitic, shallow-inland-sea iron formations (SCOS-IFs) are characterised by oolitic ironstones composed of hematite, goethite, chamosite and siderite. Gangue minerals may include detrital quartz, calcite, dolomite and apatite. The ironstones are interbedded with shales and quartz sandstones containing sedimentary features that indicate an agitated, shallow marine depositional environment (Kimberley 1978).

Although most SCOS-IF deposits are predominantly Phanerozoic in age, Mesoproterozoic oolitic ironstone deposits that are almost identical to the Roper deposits are found in the Constance Range area in northwestern Queensland (Harms 1965). They occur within the Train Range Ironstone Member, which is equivalent to the Sherwin Formation (Plumb and Derrick 1975). This remarkable correlation lends significant weight to the theory that the development of oolitic (chamositic) ironstones commonly coincided with global marine transgressions (Van Houten and Purucker 1984); a similar hypothesis has also been proposed for the large Precambrian BIF deposits (Simonson and Hassler 1996).

There has been many theories published on the origin of oolitic iron formations over the last century (see Kimberley 1978 and 1989b). The most appropriate model seems to involve the mechanical accretion of iron-rich gelatinous coats onto nuclei of fine quartz or rock fragments during gentle rolling on the sea floor, during a period of reduced sediment influx. The iron-rich solutions may have been derived from volcanogenic or hydrothermal effusive processes. During marine transgressions, the iron-rich (deeper?) waters occupied a shallow shelf or embayed coast environment (**Figure 21**) that allowed extensive production of chamositic and hematitic ooids.

During diagenesis of the chamositic and hematitic ooids, reducing conditions prevailed and they were cemented and replaced to varying degrees by siderite. The secondary silica (chert) cement may be a by-product derived from the replacement of chamosite by siderite. Fine specular hematite may have formed via hydrothermal fluids associated with intrusion of the Derim Derim Dolerite.

Distal hydrothermal deposits

Some 33 distal hydrothermal occurrences (excluding the Tennant Creek Au ± Cu ironstones) are recognised in the Northern Territory. These iron deposits are largely found within metamorphosed Palaeoproterozoic ferruginous clastic rocks in the Pine Creek Orogen, Tennant Inlier (Tennant Creek mineral field) and northern Arunta province. In the Pine Creek Orogen, a number of iron ore deposits in the Rum Jungle mineral field and Frances Creek iron field were discovered by the BMR during reconnaissance prospecting and regional geological mapping (Sullivan and Iten 1952, Crohn 1961a, b, Dunn 1962a). There is very limited geological information available on iron deposits in the Rum Jungle area, but many deposits in the Frances Creek iron field were drilled and several were mined between 1966-1974. This has resulted in good geological information being available, although very little is published.

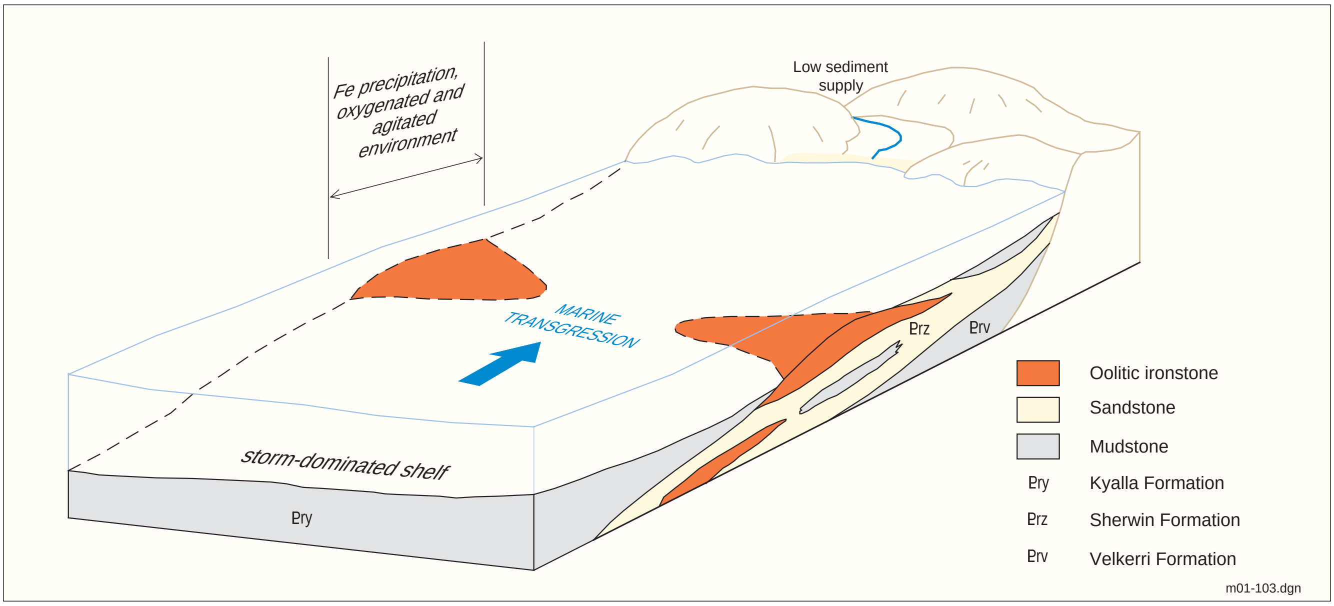

Figure 21. Schematic model for development of SCOS-IF-type iron ore deposits

Some 120 Tennant Creek ironstones have mined for gold and copper over the last sixty years. Details on characteristics, controls and genesis of the ironstones well known and widely published, but information on the iron ore potential of this region has not been previously documented. In the Arunta province, ironstones in the vicinity of Harverson Pass (NAPPERBY) have been investigated as a potential host for Au-Cu mineralisation, but only limited details are available on iron ore potential.

Pine Creek Orogen

Frances Creek iron field

The Frances Creek iron field commences about 23 km north of the Pine Creek Township and extends northward for 25 km along a series of undulating hills and ridges. Some 30 named iron prospects and mines lie within a series of discontinuous, stratabound gossanous ridges (up to 25 m high) within hematitic and carbonaceous shales and slates of the lower Wildman Siltstone (**Figure 22** and **23**). The Allamber Springs Granite outcrops to the south and probably underlies the southern part of the Field at a relatively shallow depth. Pre-tectonic dolerite dykes and sills assigned to the Zamu Dolerite are common in the local mine sequence.

Massive hematite lenses at Frances Creek were first publicly reported in 1961 (Crohn 1961a) and were mined by Frances Creek Iron Mining Corp Pty Ltd between 1966-74. These mines produced some 7.98 Mt of ore grading 59% Fe (Bagas 1981). A historical account of the project and people involved, from discovery and development to mine closure is given by Barrie (1999). Deposits Helene 1 to 10 lie within mining reserve RO 1329 (AN 389) on Ban Ban Springs pastoral lease.

Early exploration (1962-63) concentrated on the discovery site at Ochre Hill, then moved to higher grade lenses in the southern part of the field. A pre-mining resource of 5.14 Mt grading 64% Fe was estimated for the southern part of the field (Elliot 1965). Mining was not undertaken in the northern part of the field due to the lower ore grades (60% Fe) and higher levels of phosphorus (0.2%). Some 300 000 t of iron ore fines remain in a stockpile near the old crusher site (N McCleary, Arafura Resources, pers comm 1999). The remaining resources in the southern and northern parts of the field are outlined in **Table 6**. If a ≤0.09% P and >59% Fe cut-off grade for ore is applied, then a possible resource of 1.36 Mt @ 63% Fe and 0.07% P is indicated.

Complex folding has influenced the distribution and thickness of the iron ore lenses (**Figure 24**). A distinctive thickening of massive hematite lenses is common within fold hinges, particularly in synclines. Crohn (1968) noted that shallow to moderate plunges in the folds coincided with the topography in places, so that ore remained within 25 m of the surface for some 250 m down dip from outcrop. However at some deposits, subvertical dips (60-70°) made economical mining of the ore difficult beyond a depth of 50 m, despite reasonable ore widths (20-30 m).

Pre-ore bedding-plane faults and local thrust faults have produced brecciation in the ore lenses and hanging wall sequence in many deposits. A southwesterly verging thrust was mapped in the upper levels (RL 800 to 900 ft) at Helene 6/7 (Barrell 1969) and this has displaced the ore lens about 15 m to the northeast. Shale and slate clasts in the breccia zones invariably contain the penetrative regional S_1 cleavage of Stuart-Smith *et al* (1987) and this suggests that thrust faults are syn- to post-D_1. Hematite mineralisation is essentially undeformed (ie post-D_1).

Very fine, commonly carbonaceous quartz-sericite slate is the dominant host rock, but in most deposits, it is bleached adjacent to the iron ore lodes (**Figure 27**), particularly in the hanging wall sequence. Banded hematitic shale is present in and below the main ore horizon. In some deposits (eg Helene 3, 5 and Thelma-Rosemary), a second, thinner ore bed is present below the main ore bed. Peloidal sedimentary ironstone has been identified in the mine sequence at Helene 10 (NTGS sample 9556) and marble has been

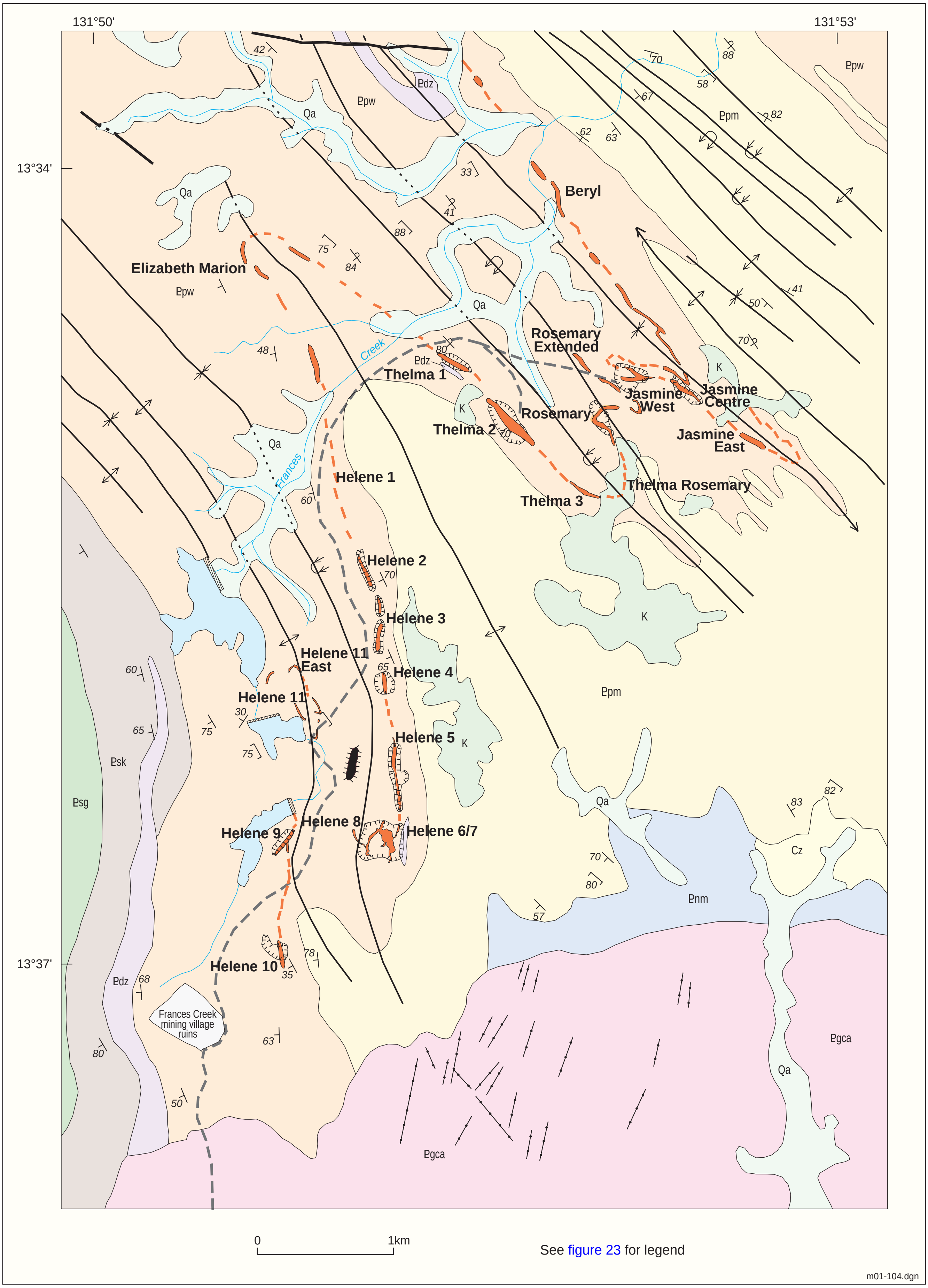

Figure 22. Geological setting of southern portion of Frances Creek iron field (modified from Stuart-Smith *et al* 1987)

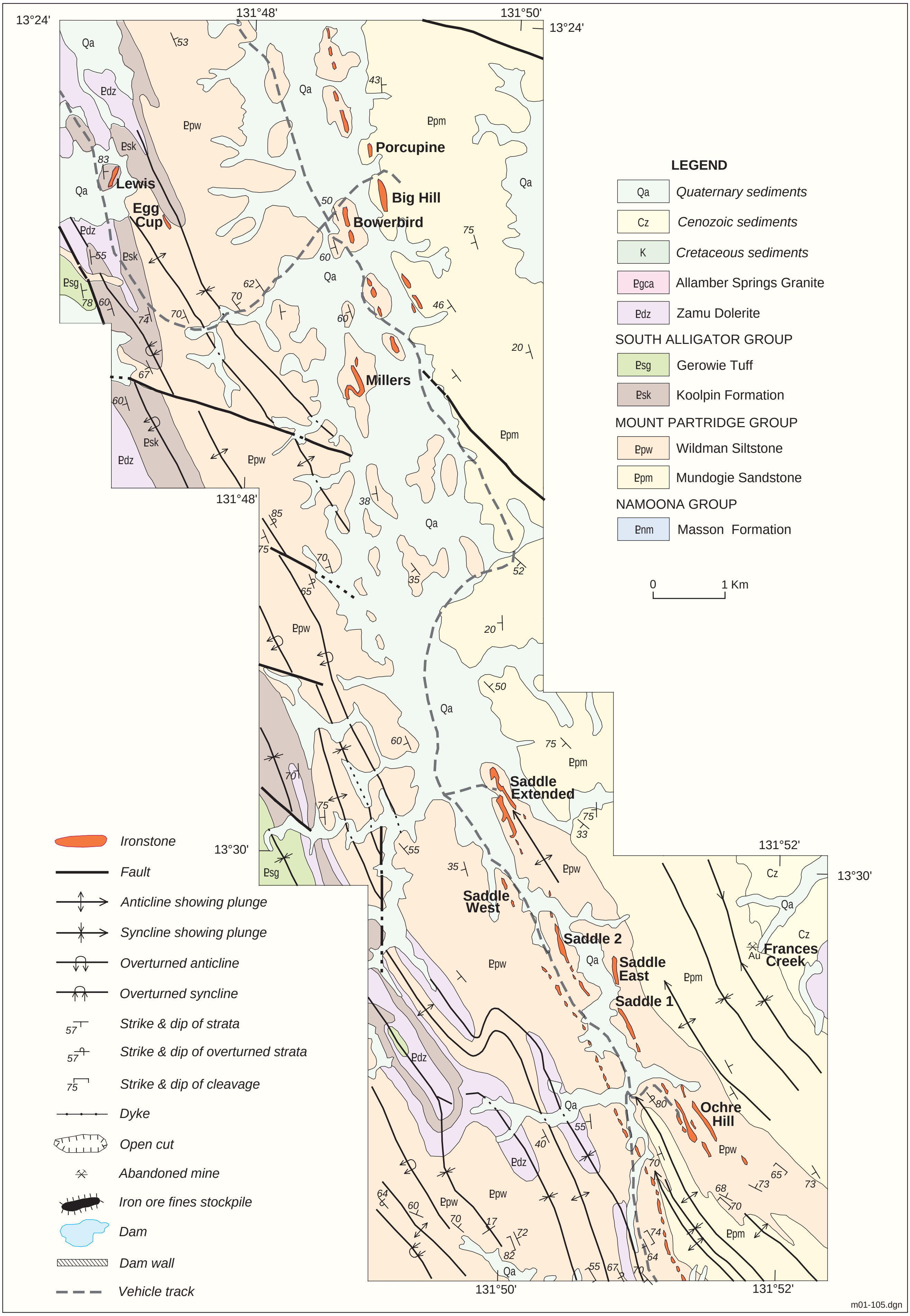

Figure 23. Geological setting of northern portion of Frances Creek iron ore field (modified from Stuart-Smith *et al* 1986)

Table 6. Identified remaining iron ore resources in the Frances Creek iron field. *Note that tonnage figures for mined deposits assumes that only a small amount of mining was undertaken between May 1974 (visit by P Crohn) and July 1974 (last shipment of iron ore from Frances Creek)

Deposit	Tonnages (t)	Fe (%)	P (%)	Strip ratio (ore: waste)	Reference	Comments
Southern area						
Helene 2 (Nth)	30 330	62.3	0.05	1:1.4	Crohn 1974	
Helene 3	*66 000	64.9	0.074	1:0.7	Crohn 1974	
Helene 4	*25 000	60.2	0.068	-	Crohn 1974	
Helene 6/7	*600 000	65.4	0.05	1:1.5	Crohn 1974	Between RL 620' and 560'
Helene 9	57 400	60.3	0.17	1:0.7	McKenna 1973	High P
Thelma 1	*65 000	62.9	0.1	1:0.6	McKenna 1973	Pre-mine resource
Thelma 3	13 500	65.1	0.185	-	McKenna 1973	High P
Thelma-Rosemary	250 000	62.3	0.14	1:1.17	McKenna 1973	High P
Rosemary	*136 000	61.3	0.09	1:0.9	Preliminary pit plan, Sept 1974	Pre-mine resource
Jasmine West	*65 000	63.3	0.06	-	Crohn 1974	
Jasmine East	62 500	59.9	0.06	1:2.17	McKenna 1973	
TOTAL	1 370 000	63.5	0.08			
Northern area						
Ochre Hill	214 000	60.2	0.09	1:0.05	Barrell 1968	
Saddle 1	217 000	57.9	0.27	-	Barrell 1968	High P
Saddle 2	50 000	57.8	0.18	-	Barrell 1968	High P
Saddle East	100 000	59.7	0.07	-	Barrell 1968	
Saddle Extended	229 000	61.5	0.25	-	Barrell 1968	High P
Miller's	1 624 000	51.7	0.09	-	Friesen 1972	7.1% Mn
TOTAL	2 430 000	54.5				

intersected within Wildman Siltstone about 1 km south of Helene 10 (Stewart and Goulevitch 1996).

Most of the ore was obtained from the *Helene No 6/ 7* open cut, which contained reserves of 6.1 Mt grading 63.4% Fe and 0.05% P (Barrell 1969). The massive, conformable hematite lode is hosted within a tight to open north-northwest-trending syncline-anticline structure that plunges moderately to the north (**Figures 24** and **25**). Significant thickening of the massive hematite lens (up to 110 m @ 63% Fe) occurred in an overturned syncline (**Figure 26**). Bowden (2000) estimated the average thickness of the deposit (based on 147 drillholes) as 15.5 m grading 64.4% Fe. Minor folds and faults, which are mineralised in places, also influence the distribution of ore. An unmineralised 40-50 m thick dolerite sill (Zamu Dolerite) is present in the footwall sequence.

Ore consists of massive, fine, micaceous to bladed hematite (**Figure 27**) containing varying amounts of shale fragments and quartz grains. Hematite is found in a number of forms; this includes veins, fine-medium interlocking anhedral aggregates, fine-medium plates or needles that may show radial growths or an 'ophitic' texture, and fine-coarse tabular crystals (**Figure 28**). Cavities within the massive ore are common and may form up to 20% of the rock, by volume. They are often lined or partially infilled with coarse, transparent, bipyramidal hydrothermal quartz crystals or by medium-grained hexagonal plates of specularite. Goethite and limonite are commonly associated with weathered ore lenses. Brecciation of the massive ore lens is evident on the eastern side of the open cut where a northwest-trending fault intersects the ore bed near the surface (**Figure 29**).

Chemical analyses of the iron ore at Helene 6/7 and other deposits is limited to early exploration rock chip sampling (Hughes and Blockley 1962, Hammond 1963) and sampling by Hamersley Iron Ltd (Bowden 2000). Chip sampling along the H5 line at Helene 6/7 averaged 65.8% Fe, 1.61% Si, 0.03% P, 0.007% S, 0.03% Ti and 0.004% Cu over 24 m (Hammond 1963). Eight samples of iron ore material from Helene 6/7 DDH 2 and DDH 8 by Bowden (2000) averaged 67.0% Fe, 2.54% SiO_2, 1.04% Al_2O_3, 0.04% P, 0.007% S, 0.05% CaO, 0.06% MgO, 0.04% TiO_2, 0.03% Mn and 0.98% LOI.

Significant resources were outlined and mined at *Jasmine* (2.34 Mt @ 61% Fe), *Thelma 2* (1.4 Mt @ 65.1% Fe) *Helene 3* (0.51 @ 65% Fe) and *Helene 5* (0.58 Mt @ 58% Fe). Further north, at *Ochre Hill*, a series of massive hematite-goethite lenses outcrop in tight synclinal structures (Barrell 1969). Initial resource estimates were 1.2 Mt @ 58.5% Fe (Barrell 1969), but follow-up drilling indicated shallow "keels" to the lenses and a revised estimate of 214 000 t @ 60.2% Fe and 0.09% P was reported by McKenna (1973). In this deposit, ore is characterised by mainly fine to medium micaceous hematite that is intergrown with, and replaced by microcrystalline goethite (Pontifex 2000).

At *Millers* Fe-Mn prospect, goethite is the dominant ore mineral; minor constituents include pyrolusite and very fine to earthy hematite (Shields 1966). Percussion and diamond drilling along the eastern section of the gossanous ironstone outlined a resource of 1.62 Mt @ 51.7% Fe, 7.1% Mn and 0.09% P (Friesen 1972), whereas the western section of the ironstone is essentially low-grade goethite (averaging 20-40% Fe). The folded ironstone bed is hosted in a sequence of arenites within the Wildman Siltstone and has developed from the surficial enrichment of ferruginous shale.

A number of iron ore pods have been investigated at *Frances Creek East*, which is about 31 km to the north-northeast of Pine Creek. These conformable ironstone bodies are within tightly folded, ferruginous carbonaceous shale and phyllite of the Masson Formation. Wandaroo Mining Corp Ltd conducted geological mapping, costeaning and percussion drilling on the largest gossan (No 1 deposit) and estimated some 1.5 Mt of low-grade ore; less than 150 000 t contains >50% Fe (Ward 1970).

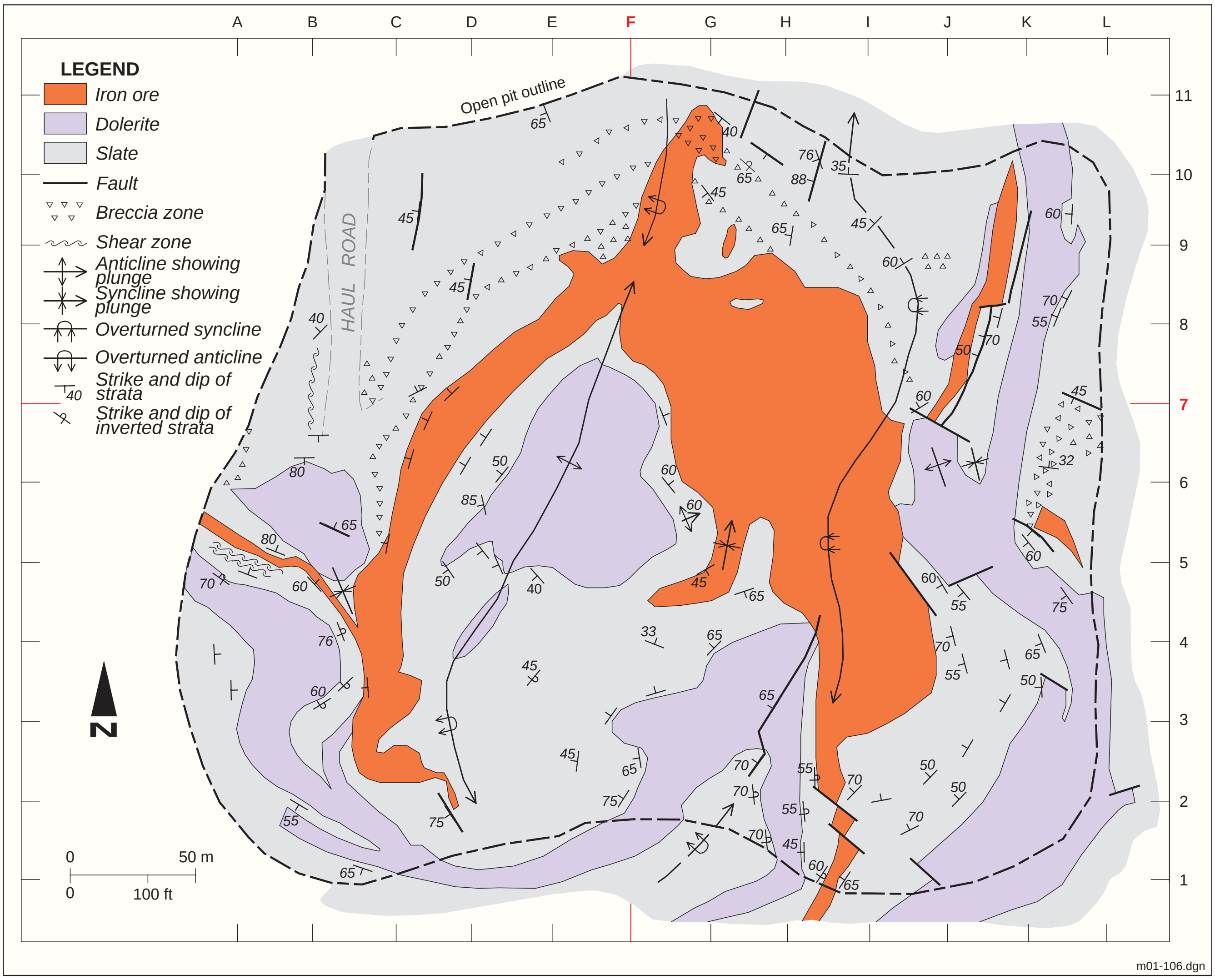

Figure 24. Geological plan of Helene 6/7 pit (modified from FIMCO mine plan G691)

The *Rum Jungle* iron ore prospect is located on freehold land about 8 km to the northwest of Batchelor and is adjacent to the Rum Jungle Inlier. Thiess Exploration Pty Ltd conducted geological mapping, costeaning, geochemical sampling and drilling programs on this prospect (Ally 1968, Burban and Svenson 1970). Four massive hematite lenses were identified; the largest (Lode B) is about 6 m thick and has a strike length of 100 m. The northeast-trending lenses are stratabound and are hosted within purple hematitic siltstone and shale of the Whites Formation (Pine Creek Orogen). Lodes A, B and C contain an inferred resource of 101 600 t grading 61.8% Fe with phosphorus averaging 0.07% at the surface and 0.14% at depth (Burban and Svenson 1970). Airtrac and diamond drilling were carried out on a 122 m (400 ft) grid. Shallow airtrac holes about 10 m apart were also drilled along costeans. Limited geochemical assays indicate that the massive hematite ore contains <0.01% S, 4.1% SiO_2, 2.7% Al_2O_3, <0.05% Cu and <0.01% Ni (Burban and Svenson 1970).

Beetson's iron ore prospect is located about 18 km to the north-northwest of Batchelor on mining reserve RO 1404 and is adjacent to the Rum Jungle Inlier. Nevsam Mining Co Pty Ltd (Pritchard 1969) and the BMR (Dunn 1962a, Crohn 1970) conducted geological mapping, costeaning and drilling in this area. The northerly-trending, stratabound gossanous lode has a strike length of 300 m and averages 20 m in width. The gossan is hosted in ferruginous shale and siltstone of the Whites Formation, and consists of irregular alternating bands of dense hematite and cavernous hematite and goethite (Crohn 1970). Two exploratory shafts were sunk near the southern end of the prospect (Pritchard 1969). Sampling of the shafts returned 63% Fe and 0.14% P over 7 m (shaft 1) and 55.2% Fe and 0.08% P over 4.6 m (shaft 2). Based on these results, Pritchard (1969) estimated a resource of 1.5 Mt grading 52-66% Fe to 60 m depth, plus 100 000 t (grading 52% Fe) of iron ore rubble around the gossan outcrop. A single line of drillholes, across the ridge and about 60 m north of the shafts, indicated that only minor amounts of iron ore material containing >50% Fe is present in this area (Crohn 1970).

The *BW Iron Claim* is a small iron ore prospect located about 16 km to the west-northwest of Adelaide River Township. Investigations by the BMR (Dunn 1962b) suggested that the stratabound massive hematite- and specularite-bearing lenses and pods are hosted in pyritic slate of the Whites Formation. A possible 15 000 t of ore grading 60% Fe was estimated for a single ironstone lens, 36x20x6 m in size. The base of this lens is truncated by a subhorizontal thrust fault. There is also about 70 000 t of loose hematite rubble present (Pritchard 1969).

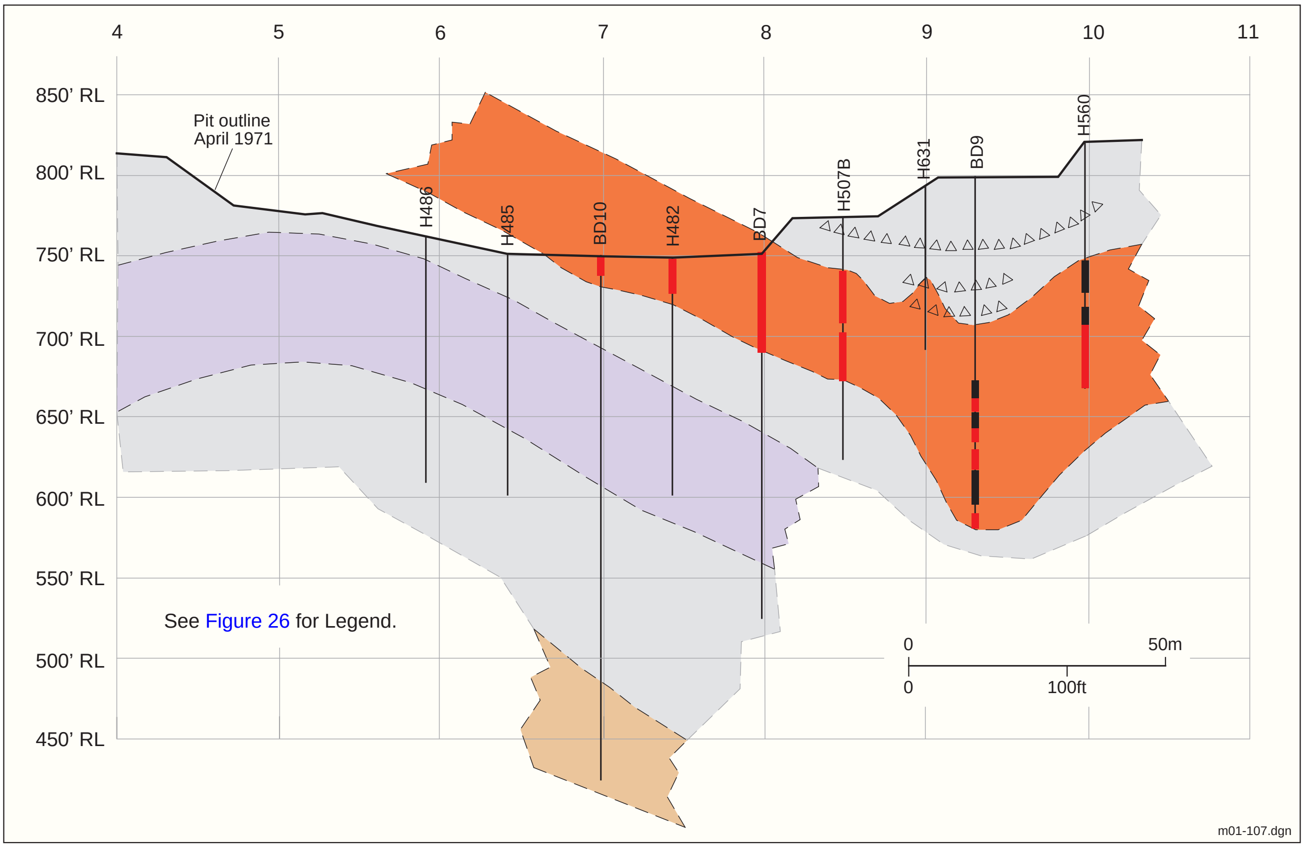

Figure 25. Longitudinal section of Helene 6/7 pit, looking west along section F (modified from FIMCO mine plan G669)

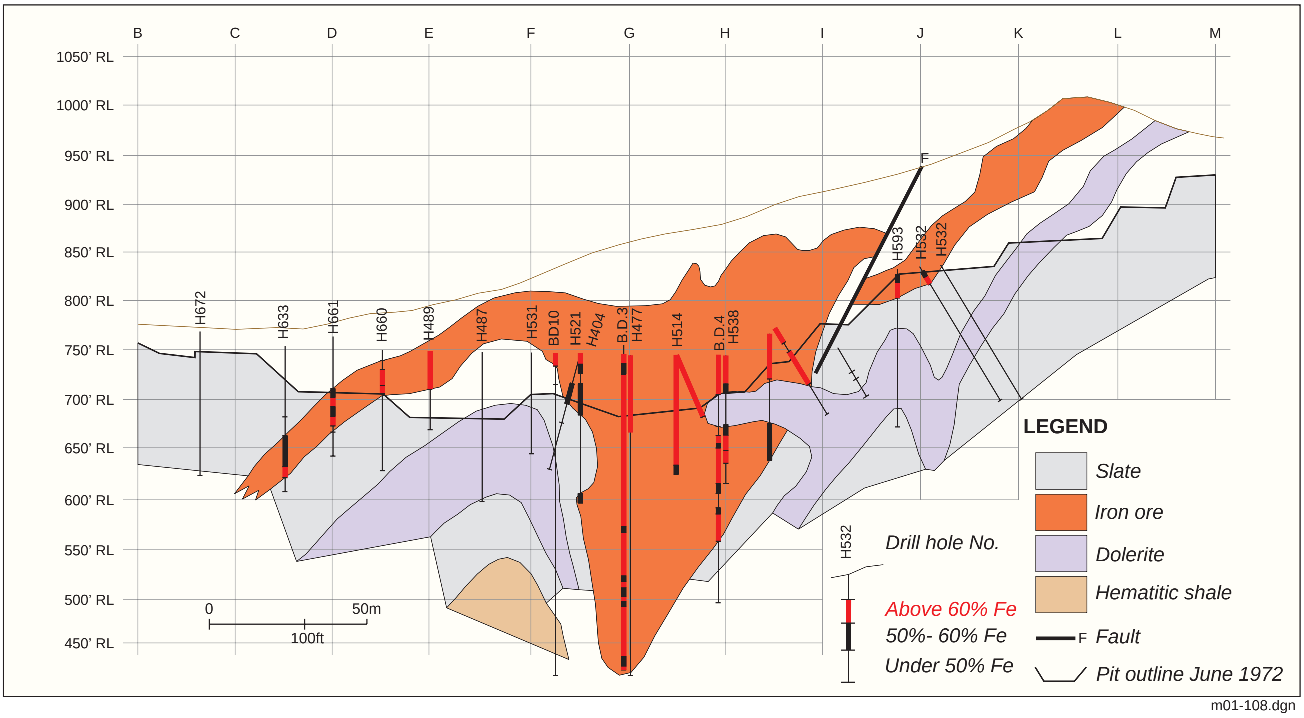

Figure 26. Cross section of Helene 6/7 pit, looking north along section 7.00 (modified from FIMCO mine plan G659)

Tennant Inlier

In the central part of the Tennant Inlier, the Tennant Creek province, ironstones form irregular ellipsoidal lenses to flattened pipe-like bodies within the Warramunga Formation and vary in size from a few tonnes to over 15 million tonnes (LeMessurier *et al* 1990). Over 700 ironstone bodies have been recorded throughout the field (**Figure 30**). Most of the

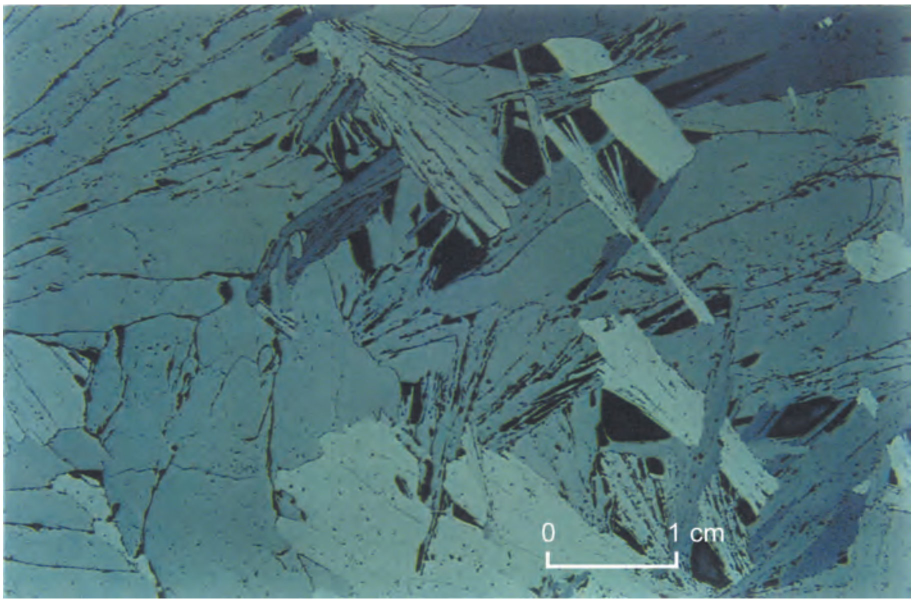

Figure 27. Polished thin section of very coarse massive specularite ore from Helene 10 at Frances Creek (NTGS 9553, cross-polarised reflected light)

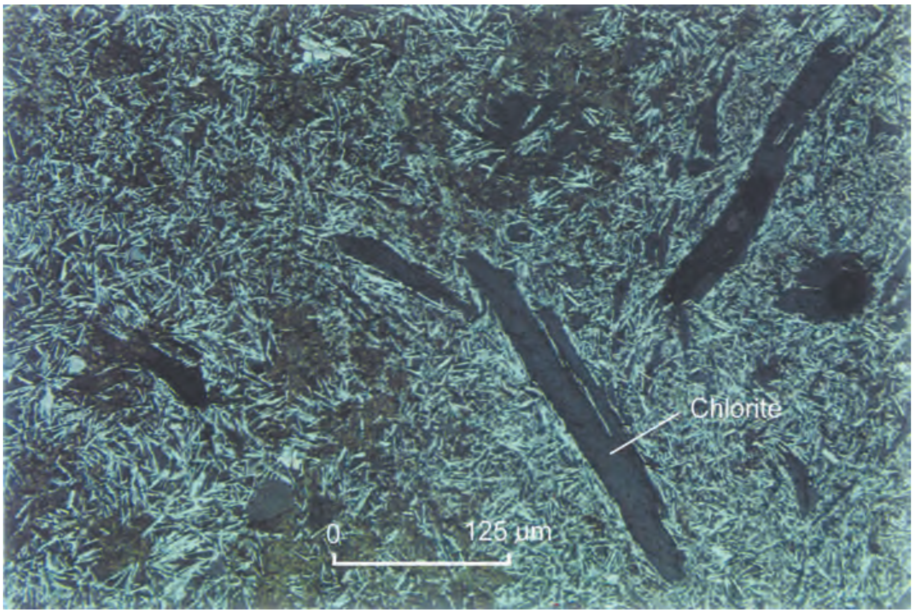

Figure 28. Polished thin section of fine micaceous hematite intricately mixed with matrix of earthy hematite and dispersed coarse flakes of chlorite from Helene 10 (NTGS 9554, reflected light)

ironstone bodies are discordant and only a few are nearly concordant with bedding. In the oxidised zone, which commonly extends to 100 m below the surface, ironstones consist of hematite and minor remnant magnetite, goethite, quartz, sericite and clay minerals. Hypogene ironstones consist of magnetite, quartz, chlorite (**Figure 31**) and minor amounts of pyrite, talc, dolomite, muscovite and calcite (Wedekind *et al* 1989).

Previous studies have recognised several significant "lines of lodes", particularly in the southern part of the field (Crohn and Oldershaw 1965, Wedekind *et al* 1989 and Rattenbury 1992). These can be traced discontinuously along east-trending directions that are sub-parallel to the Mary Lane Shear Zone. A number of structural and lithological elements, often in combination, have been found to control the distribution of mineralised ironstones.

A close surface correlation between mineralised ironstones and 'hematite shale' beds is present along the line of lodes from Mount Samuel to Rising Sun in the southern part of the field. In the subsurface, ironstones at Nobles Nob, Juno and TC8 are centred on, and partially replace hematite shale beds. In general, most of the ironstones are within argillaceous lithologies such as mudstone and shale, which are typically more strongly cleaved and fractured than the coarser arenite units, a factor which appears to make the finer rocks more susceptible to replacement by chlorite and magnetite. Other local lithological controls may include preferential replacement by ironstone along contacts between sediments and quartz porphyry intrusions (eg at Warrego and Jubilee) or within intraformational sedimentary breccias or slump structures (eg at Gecko An3 and Peko).

There are three significant trends of ironstone-bearing shear zones and faults (Crohn and Oldershaw 1965). The east trend (090-100°) is predominant and generally coincides with bedding and the penetrative S_1 cleavage orientation. The southeast (130°) and east-northeast (070°) trends possibly resulted from riedel shearing related to the D_1 event, and these trends are responsible

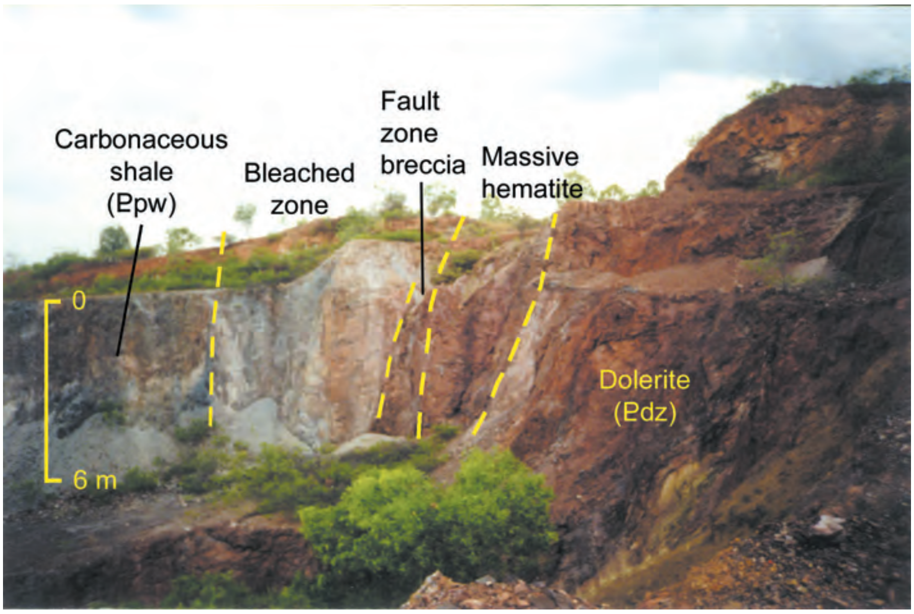

Figure 29. Bleached wallrock on Bench 5 along north wall of Helene 6/7 pit

for the irregular en echelon pattern of ironstones developed due to shear-bedding or shear-S_1 intersections.

Many deposits (eg White Devil, Black Angel, Argo, Lone Star) are located in east-trending brittle-ductile shear zones and faults, or at positions of pitch reversal within faulted anticlines and drag folds. These tight, parasitic F_1 anticlinal folds are often doubly plunging (20-40°) due to shearing that accompanied D_1. Several sub-surface deposits are hosted within anticlinal structures (eg Juno, Gecko and Peko) and this highlights these structures as favoured loci for ironstone replacement.

Chemical analyses of the Tennant Creek ironstones are essentially limited to several trace elements (Cu, Pb, Zn, Bi, Mo, Co, Sb, As, Au), which were used to assist to distinguish between mineralised and barren ironstones (Dunnet and Harding 1967, Smith 1980, Large and Robinson 1987). However, analyses performed by Smith (1980) on 973 ironstone samples did include Fe, Si, P and Mn (**Table 7**). These results indicated that the *in situ* ironstones comprise relatively low- to moderate-grade (av 51-56% Fe) iron ore material containing moderate silica (av 7.4-11.4%) and low phosphorus (av 0.01%). Many of the outcropping ironstone pods are regarded as sacred sites by the local aboriginals and are therefore unavailable for mining.

Gold and copper mining over the past 30 years has produced about 16 Mt of iron oxide-bearing tailings that may contain up to 70% magnetite. The bulk of these tailings are located at three mine sites (**Figure 30**): Warrego (45 km northwest of Tennant Creek), Peko (10 km east of Tennant Creek) and Nobles Nob (13 km southeast of Tennant Creek). These would be available for processing following negotiations with relevant stakeholders. Most of the material in the tailings has been ground to <75 micron size. There are sealed roads to each mine site and power is still connected to Warrego and Peko.

	Fe (%)	Si (%)	P (%)	Mn (ppm)
Surface ironstones (mean)	51.4	11.5	0.01	91
Surface ironstones (max)	71.0	45.0	0.20	4400
Subsurface ironstones (mean)	56.4	7.4	0.01	225
Suburface ironstones (max)	72.0	27.0	0.02	4100

Table 7. Chemical analyses of Tennant Creek ironstones (from Smith 1980)

At *Warrego*, about 5.5 Mm^3 (11 Mt) of tailings has been estimated. The retreatment of 5.3 Mt of tailings was carried out between 1994 and 1998 and this recovered 3514 kg Au. The retreatment feasibility study of these tailings indicated a mineral composition of 70.7% magnetite, 9.1% quartz, 5.8% pyrite, 7.4% chlorite, 5.3% muscovite and 0.7% calcite (Fowler and MacKay 1993). Chemical analyses indicated 33% Fe, 7% Si, 0.16% Cu and 0.05% Bi. More recent analyses of the Warrego tailings (Environmental Geochemistry International 1999) suggested 40.2% Fe (range 17-52% Fe), 15.6% Si, 1.6% S and 290 ppm P.

The *Peko* site has about 2 Mm^3 (4 Mt) of tailings containing about 70% magnetite (J Savage, Savage Resources, pers comm 1999). Analyses of these tailings indicates 43% Fe (range 31-50% Fe), 10.5% Si, 3.9% S and 280 ppm P (Environmental Geochemistry International 1999). The *Nobles Nob* treatment plant processed mainly oxide gold ore and has about 1.2 Mm^3 (2.4 Mt) of tailings. Analyses of these tailings indicates 36% Fe (range: 20.5-60% Fe), 11.4% Si, 1.0% S and 330 ppm P (Environmental Geochemistry International 1999).

In order to achieve a marketable product, processing of the Tennant Creek tailings for iron ore would require separation of magnetite and hematite from sulfides (mainly pyrite) and silicates (quartz, chlorite and mica). Similar ore material is processed at the Savage River iron ore mine in Tasmania, by crushing and grinding magnetite-pyrite-silicate ore (containing about 47% magnetite) to 85% <43 micron grainsize. These fines are then fed through magnetic separators to produce an iron ore concentrate grading 68.0% Fe (Langenberg 1993). Alternatively, the magnetite fines could be also be marketed for coal cleaning/washing purposes to operations that use heavy medium bath units. Size specifications are in the order of 95% <105 microns, whereas specifications for magnetite used in dense-medium cyclones are 95% <53 microns (Pratt 1978).

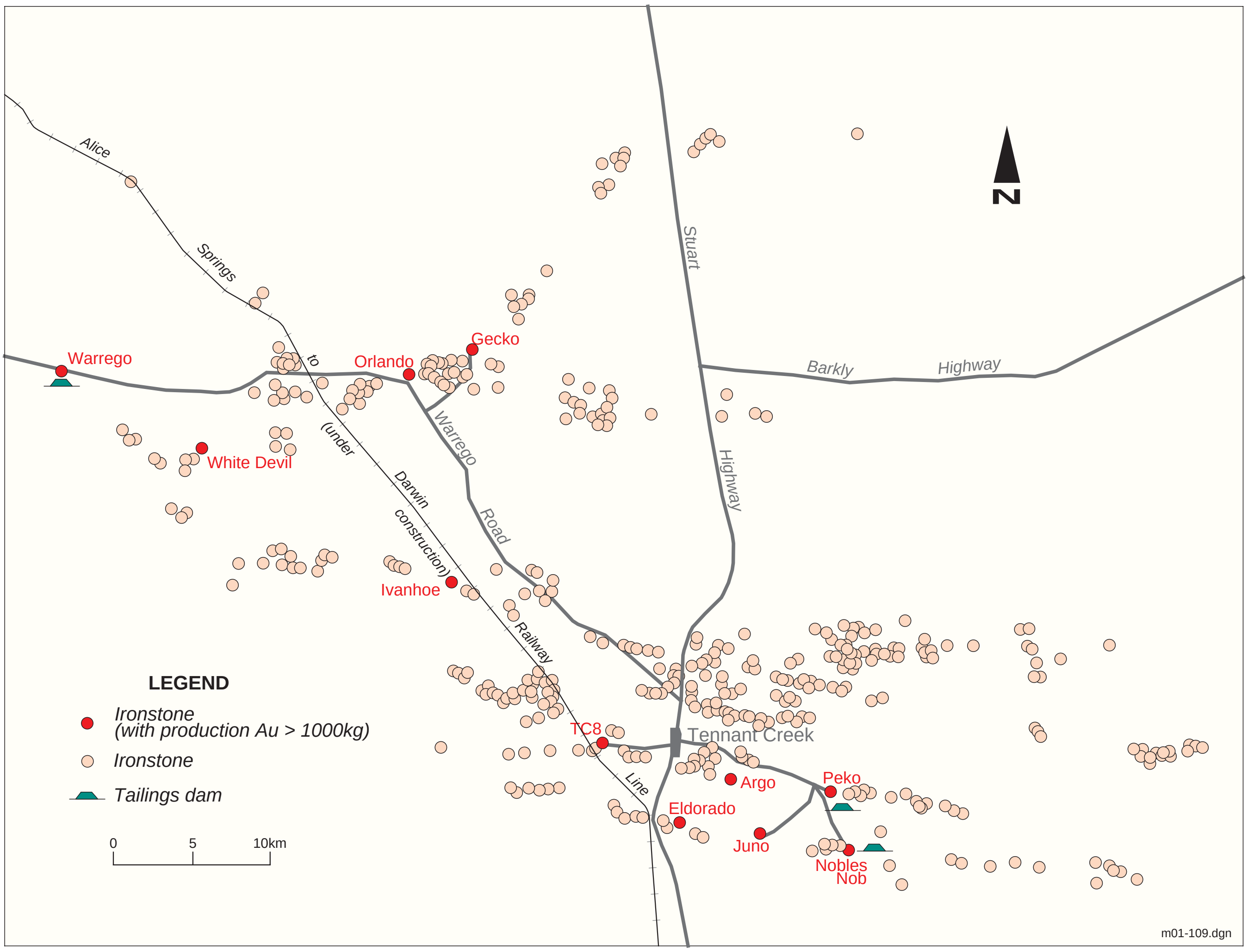

Figure 30. Distribution of ironstones in Tennant Creek mineral field (modified from Wedekind *et al* 1989)

Arunta province

Small massive hematite lenses are present within the Mount Thomas Quartzite on the Pine Hill pastoral lease in the Harverson Pass area on Reynolds Range (Stewart 1982). Reconnaissance mapping indicates lenses are up to 15 m thick and can be discontinuously traced over 10 km along strike (Lindsay-Park 1998). The hematite contains quartz veinlets and is present as massive to bladed (specularite) aggregates. Massive hematite (± quartz) lenses grade laterally into coarse chert ironstone and hematitic quartz arenite.

In the type section of the Mount Thomas Quartzite (at AMG 277130mE 7531670mN), Stewart (1982) reported a lens of massive hematite, several metres thick, at the contact with a sill of granitic orthoschist (Warimbi Schist). In other localities, hematite lenses are present at the contact with the overlying and interfingering Pine Hill Formation. The genesis of the ironstone lenses is uncertain, but may be related to high temperature regional and contact metamorphic events that have affected the hematitic beds of the Mount Thomas Quartzite (Stewart 1982).

Ore genesis

Earlier interpretations on the genesis of the Frances Creek iron ore deposits were based on brief inspections of the Helene 6/7 pit (Johnston 1984, Stuart-Smith *et al* 1993) or on observations made prior to mining (Crohn 1968). A supergene model was proposed, in which pyritic shale breccia within early (pre-D$_1$) thrust faults was oxidised and enriched to produce hematitic ironstones. A more recent review of mining data (geological plans and cross-sections) along with petrological studies and field inspections of the open pits (Pontifex 2000) suggested that the iron ore mineralisation is the result of hydrothermal remobilisation (Bowden 2000). In this model, iron oxides from ferruginous banded shale in the Wildman Siltstone were concentrated into favourable structural sites that developed prior to the intrusion of the Allamber Springs Granite.

Examination of mining plans and sections of the southern Frances Creek iron ore deposits indicates that iron ore continues below the pit floor and also below the weathering profile, which can extend down to 80 m below the surface in this area. Intersections of massive hematite with no visible sulfides 130 m below the surface (eg Helene 6/7 drillhole BD 3) cannot be accounted for by the oxidation of pyritic breccia. Wallrock adjacent to ore lenses in upper and lower parts of the deposits is commonly bleached and this suggests hydrothermal fluid activity. Hydrothermal processes can also account for massive iron oxide mineralisation that is hosted in places within altered microdolerite (Zamu Dolerite).

The involvement of a low-temperature hydrothermal system is also indicated by ore mineral textures, such as

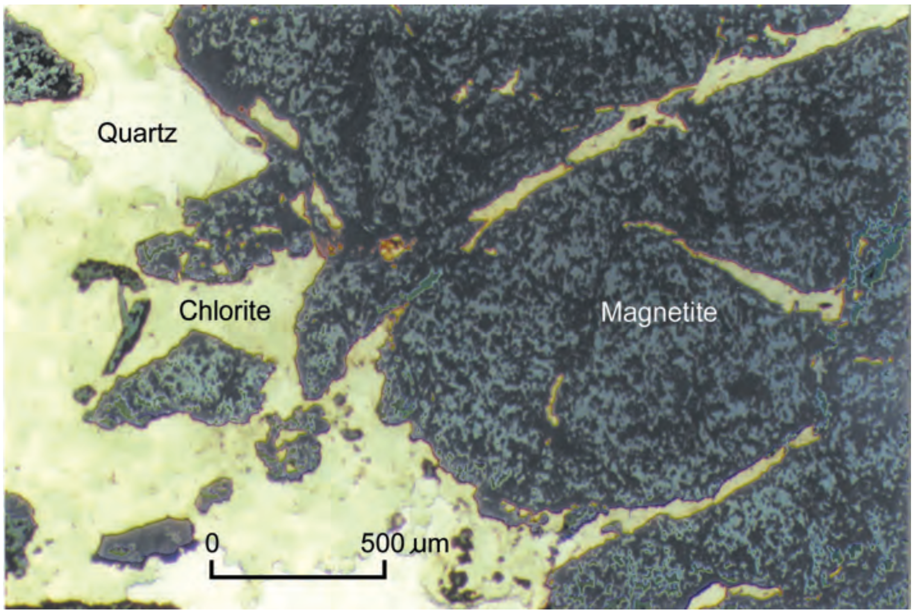

Figure 31. Polished thin section showing magnetite-chlorite-quartz assemblage in ironstone from TC8 mine (DDH TC8/5 at 126.8 m depth, partly reflected and transmitted light)

microplaty to coarse bladed hematite (specularite) and euhedral authigenic quartz, by complex massive replacement textures and by vugs, breccias and veins. Griffin (1981) has described similar iron ore mineralisation (hydrothermal specularite) at Koolyanobbing in Western Australia. Fluid inclusion studies on quartz within the specularite mineralisation at Koolyanobbing indicate hydrothermal temperatures between 110°C and 230°C. A similar temperature range is envisaged for the formation of the Frances Creek iron ore.

Shear and breccia-filled fault zones of different scales and generations are present in the Frances Creek deposits. Pre-ore bedding-parallel faults and thrusts are the main structures and these appear to have provided permeable pathways for the hydrothermal fluids. Tight F_1 folding in the sequence produced low pressure (or permeable) zones in fold hinges that were favourable loci for iron ore concentration.

A progressive increase in goethite content and phosphorus levels in iron ore deposits to the north is probably related to greater distance from the Allamber Springs Granite, which is the likely heat source for hydrothermal fluids. Stratabound ironstones have also developed in the Koolpin Formation, adjacent to the Allamber Springs Granite near McCarthys Hill (on Ranford Hill) and the Burnside Granite near Ban Ban Springs on Mckinlay River.

Various authors (Large 1975, Wall and Valenta 1990, Wedekind *et al* 1989, Huston *et al* 1993, Skirrow 2000) have discussed the genesis of the Tennant Creek ironstones. These ironstones probably evolved from 200-300°C calcic brines during regional deformation and intrusion of the Tennant Creek Supersuite. Iron oxides precipitated in dilatant zones and commonly replaced highly strained and chemically reactive shale beds to form irregular massive pods and pipes.

Skarn deposits

Skarn Fe deposits are recorded in the Pine Creek Orogen and Arunta province. The former hosts the relatively well known Mount Bundey deposits to the southeast of Darwin. The northern Arunta province hosts the Murray Creek garnet-magnetite skarn. Little information exists on this occurrence, which has been drilled by CRA Exploration Ltd (Harvey 1982).

Pine Creek Orogen

Several magnetite-bearing ironstones are present in the vicinity of the Mount Goyder Syenite, about 95 km to the southeast of Darwin. The most prominent of these is the Mount Bundey iron ore deposit. Other occurrences include Anomaly A, Anomaly B1 and Anomaly G1.

Mount Bundey iron ore deposit

The Mount Bundey iron ore deposit is located adjacent to the Arnhem Highway, about 90 km to the southeast of Darwin (**Figure 5**) and is within mining reserve RO 1366. It was discovered in 1956 during a regional mapping survey by the BMR (Dow and Pritchard 1958). Subsequent mining of the deposit between 1968-1971 produced some 534 775 t of iron from 843 063 t of ore grading 63.43% Fe, 0.108% S and 0.057% P_2O_5 (Ryan 1975). The following summary on the geology of this deposit is largely based on work of Ryan (1975) and on drill core and field observations.

The concordant, tabular ironstone bodies are hosted within a roof pendent of near-vertical metasediments of the Wildman Siltstone within the Mount Goyder Syenite. Two groups of lodes were mined. The eastern group trends northeast and dips subvertically (60-80°) to the southeast. It includes the Main (Pritchard's) Lode and the Parallel Lode (**Figure 32**). The western group diverges from the southern section of the eastern group and follows a northerly trend.

Most of the iron ore was extracted from the eastern group and from rubble and scree adjacent to the lodes. The Main Lode is about 700 m long and up to 32 m wide, whereas the overlying Parallel Lode is 2-9 m wide (**Figure 33**). Both lodes were mined along the length of the deposit down to the sulfide-bearing zone (>1% S), which is at about 20-25 m depth.

The ironstone bodies consist of massive medium to very coarse (0.2-10 mm) martite with varying amounts of hematite,

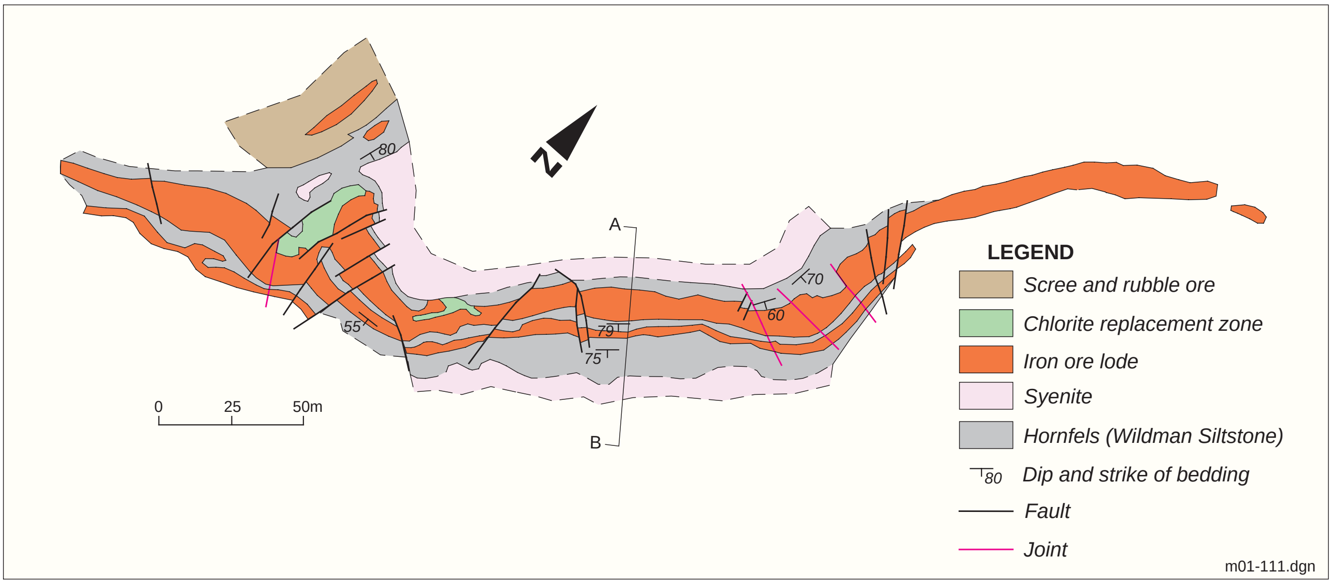

Figure 32. Geological map of Mount Bundey iron ore deposit (modified from Ryan 1975)

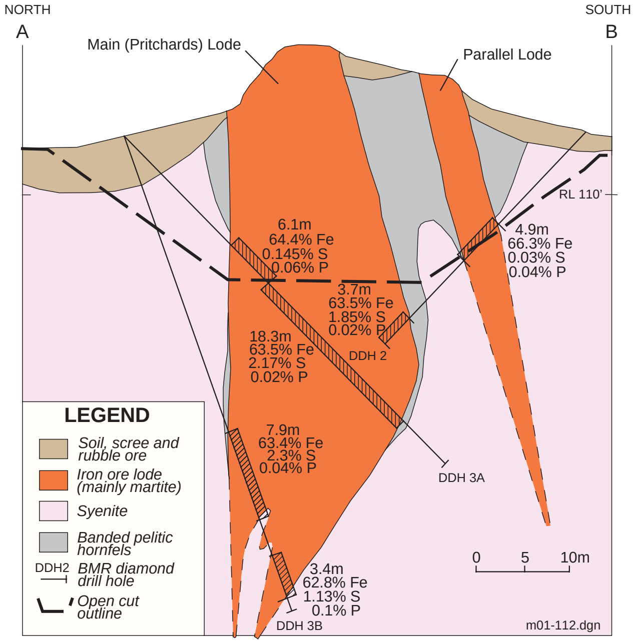

Figure 33. Geological cross section of Mount Bundey iron ore deposit (modified from Dunn 1964)

goethite and quartz near the surface. Below the zone of oxidation (25 m), a martite-magnetite-pyrite association, which contains minor chalcopyrite (<1%), is present. Pyrite averages 2-5%, but may constitute of up to 20% of the ore in places. Vugs are common in upper parts of the martite ore and probably represent voids after leached-out sulfides.

Thinly bedded ferruginous shale, mica schist, chlorite-mica schist and hornfels host the massive iron ore lenses and veins. An early K-feldspar alteration (K metasomatism) in the hornfels is overprinted by a hydrothermal chlorite-magnetite-pyrite alteration (**Figure 34**). Aplite dykes and veins as well as diffuse zones of hydrothermal chlorite crosscut the ironstones and metasediments. The syenite is also hydrothermally altered (chloritised) and contains veins and disseminations of magnetite and sulfides.

Orridge (1993c) estimated an inferred resource of 190 000 t of ore grading 62% Fe and 0.8% S that exists to a level 10 m below the pit floor. Surrounding the open cut are several irregular dumps containing iron ore material intermixed with waste rock and surficial sediments. A survey of the old dumps and stockpiles indicated a volume of approximately 164 000 cubic metres (Orridge 1993c). A composite sample of the iron ore material present in the dumps and stockpiles assayed 62.55% Fe, 0.14% S, 0.05% P and 5.45% SiO_2.

A small martite lode (known as *Anomaly A*) is present about 250 m to the northwest of the main open cut. Two BMR diamond drillholes (DDH 6 and 7) intersected only minor amounts of iron ore (Dunn 1964). Follow-up ground magnetic surveys suggested that a strong 350 m north-south magnetic anomaly is present and this may contain a possible 100 000-200 000 t of iron ore at between 0-25 m depth (Orridge 1993b). The *Anomaly B1* prospect is located about 2 km to the north-northeast of the Mount Bundey open cut and consists of a 500 m long, north-south trending magnetite body about 15-30 m below the surface (Orridge 1993c). The *Anomaly G1* prospect is located about 8 km to the east of the Mount Bundey open cut. It has a very similar magnetic signature to the Anomaly A body, indicating that a possible 100 000 t of iron ore may be present (Orridge 1993b).

Ore Genesis

Ryan (1975) suggested that the iron ore (magnetite-pyrite) lodes were essentially formed by the remobilisation of sedimentary iron within the metasediments during intrusion of the Mount Goyder Syenite, and that martite formation essentially occurred during a pre-Cretaceous supergene enrichment period. However, this model does not explain the presence of magnetite-pyrite lodes that extend into hydrothermally altered syenite, as observed in some of the deeper drillholes (eg DDHs 3B, 4A and 6). It also does not explain the overprinting of an early K-feldspar

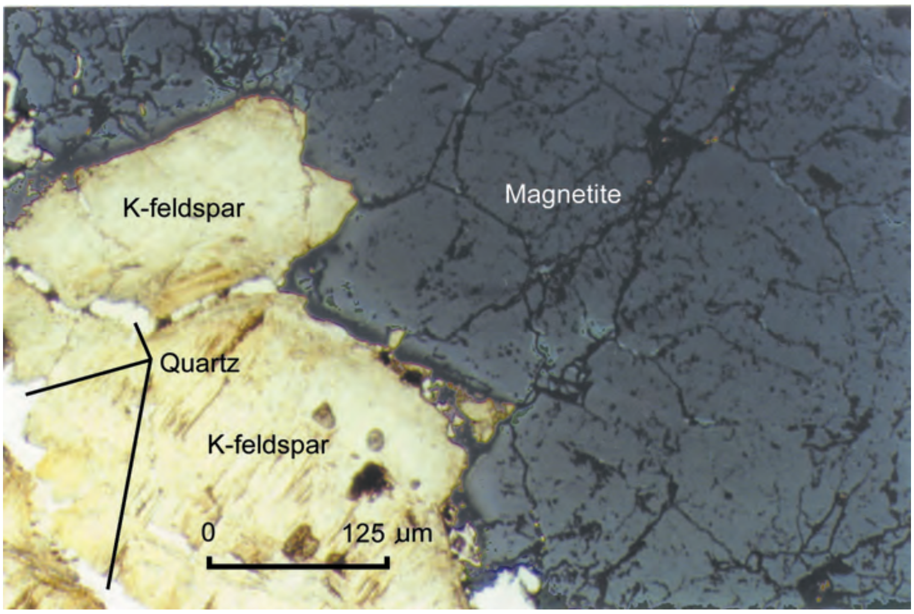

Figure 34. Polished thin section showing coarse hydrothermal magnetite replacing chloritised K-feldspar (altered syenite) at Mount Bundey mine, from DDH 10 at 29.56m depth (NTGS MB09, partly reflected and transmitted light)

metasomatic assemblage, formed during intrusion of the syenite, by a chlorite-magnetite-pyrite alteration assemblage in hornfels associated with the Mount Bundey Granite.

The Mount Bundey igneous suite (1831 ± 6 Ma) consists of a composite pluton of shoshonitic Mount Goyder Syenite and calc-alkaline Mount Bundey Granite, plus associated lamprophyre dykes and later felsic and aplitic dykes (Sheppard 1995). The contact between the syenite and granite is sharp and intrusive; several exposures indicate that the granite is younger (Sheppard 1992).

Quartz-pyrite-magnetite veins, 2-10 cm thick (**Figure 35**), are present in the Mount Goyder Syenite at the Halkitis quarry, which is 1.5 km south of the Mount Bundey deposit. It is probable that these veins are related to the intrusion of the more voluminous Mount Bundey Granite, which is likely to underlie the Mount Goyder Syenite beneath the iron ore deposit. A chlorite and hematite alteration halo adjacent to the veins is also present in the syenite wall rock. These quartz-pyrite-magnetite veins have not been identified in the Mount Bundey Granite (Sheppard 1992).

Similar features are present at the Mount Bundey iron ore deposit, but on a larger scale. Magnetite-Fe (Cu) sulfide veins crosscut and replace altered syenite and pelitic hornfels. The latter has been substantively replaced by hydrothermal magnetite, as it is permeable (well cleaved and bedded) and contains chemically reactive fine-grained micas. Bedding-parallel faults within the metasediments may have also acted as favourable hydrothermal channels. It is possible that the host sediments may have contributed a significant portion of iron to the deposits (cf Frances Creek iron field) as suggested by Ryan (1975). The magnetite-pyrite ore was subsequently 'upgraded' during a period of supergene enrichment to produce the massive vuggy martite ore.

Figure 35. Magnetite vein in Mount Goyder Syenite, east face of Halkitis Quarry (hammer length is 0.4 m)

Surficial deposits

Some 38 surficial iron occurrences are recognised across the Northern Territory and these are hosted by a variety of rock types and structures. Small tonnages have been outlined in unconformity-related deposits in the Pine Creek Orogen (Daly River Road) and McArthur Basin (Tawallah Range). Other occurrences are entirely due to surficial enrichment of ferruginous sediment and these include deposits in the Arafura Basin (Elcho Island), McArthur Basin (eg Murphy's) and Arunta province (eg Woodforde River Ironstones). Only limited information is available on many of the occurrences due to a lack of exploration work. Brief descriptions of some known prospects and occurrences are given below.

Pine Creek Orogen

The *Daly River Road* deposit is located about 25 km to the south of Adelaide River Township, on perpetual lease crown land (NT Por 4724), near the western edge of a prominent mesa composed of flat-lying Cretaceous sediments. Wandaroo Mining Corp Ltd (1968), BMR (Daly 1969) and Kratos Uranium NL (Sullivan 1970) conducted exploration work on the prospect and this included geological mapping, rock geochemistry, and percussion and diamond drilling. The ironstone lenses are near the base of a highly lateritised sequence of Cretaceous claystone porcellanite, siltstone and sandstone that is capped by remnants of nodular laterite (Daly 1969).

This succession unconformably overlies Mesoproterozoic quartz arenite of the Depot Creek Sandstone (Victoria-Birrindudu Basin). The poorly exposed ironstone occurs as dark red boulders of varying size and as limited outcrops in creek beds or at waterfalls. In the sub-surface, the ironstone forms lenses up to 650x250x1.2 m in size (Sullivan 1970). Fibrous goethite is the main ore mineral and there is minor lepidocrocite and limonite, often in the form of cavity-filling fine colloform or concretionary bands. An inferred resource of 900 000 t grading about 50% Fe was estimated by Sullivan (1970).

Minor secondary ferruginous deposits have been noted at unconformities in the vicinity of Mount Tolmer and Mount Mabel. At *Mount Tolmer*, a massive ironstone body is situated at the unconformity between the Mesoproterozoic Depot Creek Sandstone (Victoria-Birrindudu Basin) and Palaeoproterozoic Burrell Creek Formation (Crohn 1964). It consists of a dense, fine-grained, high-grade variety of hematite (61.8% Fe) and a low-grade cellular form (56.7% Fe) that contains minor limonite. In the vicinity of Mount Mabel, gossanous ironstones have developed over ferruginous sandstone beds in the Depot Creek Sandstone and over adjacent banded iron formations assigned to the Archaean Waterhouse Complex (Dunn 1962a).

A sandy laterite ore composed of goethite and limonite has developed over the Coomalie Dolomite at *Yarram* (AMG 714830mE 8563660mN) near Batchelor and this contains an inferred resource of 8.8 Mt grading 40-50% Fe and 0.16% P (Burban and Svenson 1970). Limited geochemical assays indicate that the laterite material averages <0.01% S, 4.1% Mn, 8.5% SiO_2, 4.7% Al_2O_3, <0.05% Cu and <0.01% Ni.

The *Howley* iron prospect is located adjacent to Dorat Road, about 8 km to the northwest of the Hayes Creek Inn. Several conformable, massive hematite gossans are present within the Koolpin Formation, adjacent to a 13 m thick sill of Zamu Dolerite. Surface sampling of the main ore lens, which measures 580 m in length and up to 12.2 m in width, indicated a grade of 52.12% Fe, 0.14% Mn and 0.12% P_2O_5 (Murphy 1968). A diamond drillhole sunk by the BMR (Sullivan and Iten 1952) suggested that the gossan caps a 14.5 m thick, pyritic dolomite bed that has undergone a significant amount of surficial enrichment in the upper 20 m.

McArthur Basin

Several iron occurrences occur within the basal part of the Mallapunyah Formation of the McArthur Basin, in the Tawallah Pocket area, which is about 30 km to the north-northwest of Billengarrah Homestead. The largest reported occurrence is at the *Tawallah Range* prospect (TAWALLAH RANGE, AMG 571630mE 8243070mN). This deposit consists of two hematite-rich beds that dip about 25° to the north within a faulted synclinal structure. The two beds have an aggregate thickness of about 4 m and a strike length of 1000 m, and it is estimated that they contain some 12 Mt of iron ore grading 37-40% Fe (Johnston 1974).

Laminated and ‘fenestral’ textures within some of the massive hematite ore is suggestive of the replacement of carbonate (Haines in Pietsch *et al* 1991). The close proximity of the Cretaceous unconformity and of various faults to this and the other occurrences suggests that they may have been produced by intense ferruginisation of the basal fine dolomitic sandstone by oxidising Fe-rich groundwaters percolating along the unconformity. It is also possible that the Fe-rich surficial fluids may have been derived from the leaching of uplifted, adjacent mafic volcanic units (Gold Creek, Settlement Creek and Seigal Volcanics).

At *Murphy’s* Fe prospect (CHAPMAN, AMG 443530mE 8376170mN), a series of concordant siliceous lenses up to 100 m long and 7 m thick contain massive to disseminated hematite and can be traced for some 1000 m along strike (Hickey 1987). Lenses are hosted in arkosic arenites of the Mount Birch Sandstone and occur at the unconformity with an underlying porphyritic rhyolite unit (Mount Reid Volcanics) near the Urapunga Granite. Bulk sampling by BHP Ltd indicated that sections of the deposit contain up to 54% Fe over 5 m and 51% Fe over 11 m (Hickey 1987).

Arafura Basin

The *Elcho Island* iron ore deposit extends for about 2.5 km along the western coastline, just to the north of Galiwinku. A lower sandy hematite layer and an upper hematitic sandstone bed are present in the upper part of a bauxitic laterite profile that has developed within the Elcho Island Formation. The massive lower hematite bed is up to 0.45 m thick and contains the bulk of the iron ore resource (600 000 t grading 60.4% Fe and 0.054% P) estimated by Rix (1964). Most of the ore lies at or near the surface, with the overburden gradually increasing to the north where it reaches a maximum of 6 m. The overlying hematitic sandstone is up to 1.2 m thick and averages 40.4% Fe and 0.57% P (Rix 1964).

Arunta province

The *Woodforde River* Ironstones occur in hills within the upper reaches of the Woodforde River, 34 km to the northwest of Aileron Roadhouse (Stewart 1982). They comprise several low-grade limonite- and goethite-bearing ironstone lenses, which have developed over marble and calcsilicate intervals (Ᵽo$_1$) within the Woodforde River beds (Stewart 1981). A chip sample from one of the ironstones at AMG 301680mE 7509910mN assayed 375 ppm Zn and 65 ppm Pb (Stewart *et al* 1980). Close proximity to granites suggests a possible skarn origin, but there are no data to test this possibility.

Several ironstone lenses, the largest being 122 m long and 6 m wide, are present at a prospect known as *Barney's* ironstone (AMG 268930mE 7531970mN), some 5 km to the southwest of Mount Thomas (Ryan 1958, Stewart 1981). The ironstones are limonitic in composition and are hosted within quartz mica schist, which is assigned to the Lander Rock Beds. The strike of the ironstones is parallel to cleavage. Their genesis is uncertain, but a surficial supergene enrichment process seems to be most likely.

IRON ORE PROSPECTIVITY

The absence of thick and extensive Precambrian BIFs significantly reduces the Northern Territory's likelihood of hosting a large, high-grade iron ore deposit. However, potential exists for large tonnage oolitic sedimentary iron ore deposits in the Roper River iron field. Small tonnage hydrothermally-enriched hematite deposits are present at Frances Creek and Harverson Pass. Mine tailings at Tennant Creek contain up to 70% magnetite and are amenable to retreatment processes.

A resource of some 60 Mt @ 50% Fe is indicated in the Hodgson Downs area (Roper River iron field), based on widely spaced drillholes and surface sampling. Further shallow drilling and subsurface sampling is required over these deposits to determine the extent of the resource and the levels of phosphorous and other impurities. If low phosphorous levels and ore continuity are established, then potential would exist for the development of a low-grade resource that may be amenable to concentration by floatation processes. Further low-grade resources (>200 Mt @ 40% Fe) of harder, higher silica material are available in the Sherwin Creek and Mount Scott areas.

A remaining resource of 1.36 Mt @ 63% Fe and 0.07% P exists at Frances Creek. Although this tonnage is quite small, substantial additional tonnages could be present under surficial sediments at shallow depths. Massive hematite pods continue at depth and appear to have a structural and stratigraphic control on their distribution. Most of the iron ore deposits (eg the Helene 1 to 10 and Jasmine deposits) lie along the flank of a strongly magnetic interval (**Figure 36**) in the upper Mundogie Sandstone. Other deposits (eg the Thelma, Rosemary and Ochre Hill deposits) coincide with magnetic lows within the Wildman Siltstone (**Figure 36**). An alternative approach for defining drilling targets would involve conducting detailed ground or airborne gravity surveys over selected areas in the southern Frances Creek iron field. This would be able to detect 1-5 Mt lenses in gently plunging synclinal structures under shallow cover. Chemical and physical testing of the existing material to determine its suitability for pigmentary iron ore could also be undertaken.

Small tonnages of iron ore are present in the Rum Jungle area that may meet the requirements for other local mineral processing uses. Untested ironstones in the Mount Bundey area have better potential for Au-Cu mineralisation than for iron ore.

Mine tailings at Warrego, Peko and Nobles Nob in the Tennant Creek area total 16 Mt @ 40% Fe and are a short distance from the pending Alice Springs to Darwin railway line. Iron is mainly in the form of liberated magnetite grains, <75 microns in size, which are amenable to concentration by magnetic separation. A metallurgical sampling and testing program is required to determine the amount of saleable iron ore concentrate that can be recovered. The existing infrastructure, power and access roads, as well as low capital costs and the new railway are factors that make tailings retreatment an attractive project.

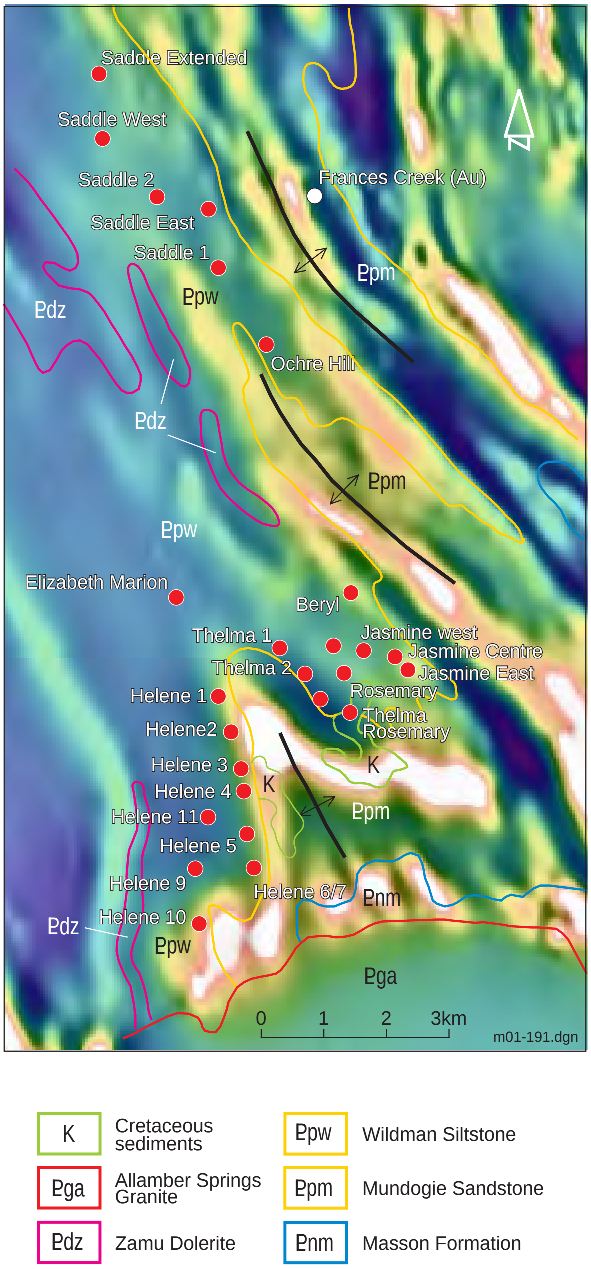

Figure 36. Magnetic signature (reduced to pole) over southern Frances Creek iron field

MANGANESE

Definition and classification

Manganese (Mn) is a transition metal with a crustal abundance of 0.1%, mainly in the form of oxides and carbonate. There are over 100 manganese minerals, but economic deposits are

Mineral	Chemical Composition	% Mn	SG	Hardness
Hausmanite	Mn_3O_4	72	4.8	5.5
Pyrolusite	MnO_2	63	4.75	6.5
Psilomelane	$BaMnMn_8O_{16}(OH)_4$	45-60	4.4-4.7	5
Cryptomelane	$KMn_8O_{16}Mn$	54-58	4.3	6
Hollandite	$BaMn_8O_{16}Mn$	45-52	4.8	6
Manganite	$Mn_2O_3.H_2O$	62	4.3	4
Braunite	$3Mn_2O_3.MnSiO_3$	62	4.8	6-6.5
Bixbyite	$(Mn,Fe)_2O_3$	30-60	4.5	5.5-6.5
Rhodochrosite	$MnCO_3$	47	3.5	4

Table 8. Properties of common economic manganese minerals

dominated by a few oxide phases (**Table 8**). Manganese carbonate has been mined from small deposits containing >90% rhodochrosite and is also present in larger deposits containing significant oxide ore. Manganese is essential to iron and steel production due to its unique sulfur-fixing, deoxidising and alloying properties. About 95% of all manganese ore produced is consumed, primarily as ferromanganese and silicomanganese, in the manufacture of steel and in other minor alloy-related industries.

Manganese deposits have formed worldwide in a variety of geological environments throughout geological time, but only a few deposits have high-grade manganese ore in commercial quantities. Roy (1981) has subdivided Mn deposits into three major categories, based on the main process of formation:

- Sedimentary (non-volcanogenic and volcanogenic);
- Hydrothermal; and
- Surficial.

This simple three-tier classification scheme can be further refined (**Table 9**) using lithological associations and host rocks (Roy 1981, Laznicka 1992).

Sedimentary deposits are the most important group in terms of past Mn production and global subaerial Mn resources. They can form along passive (Atlantic-type) continental margins (eg BIF related, carbonate-hosted or terrigenous sediment-hosted Mn deposits); active (Pacific-type) continental margins (eg volcanic island arc deposits); oceanic ridges/springs (eg greenstone-hosted deposits); and in pelagic domains (eg seafloor Mn-Fe nodules).

Hydrothermal deposits are usually of minor economic importance, as they form relatively small bodies (veins and replacements) that can be either distal or adjacent to igneous felsic intrusives or extrusives.

Surficial concentrations form under surface and near-surface weathering conditions. Mn oxides accumulate by mechanical and chemical alteration of protore material, which can be manganiferous sediments (most commonly carbonate) or sulfide ore.

The above classification system is a useful guide, but transitions exist between categories and most deposits have undergone more than one phase of Mn formation. Most subaerial manganese deposits have undergone varying degrees of supergene alteration, to produce high-grade oxide ore. Some deposits have been metamorphosed and this obscures the geological environment of the primary deposit. Refer to Laznicka (1992) for a more refined lithogenetic and quantitative approach to the classification of manganese deposits.

Although manganese deposits are widely distributed, production and resources of the metal are confined to a few countries (**Table 10**). The Kalahari Manganese Field (KMF) in South Africa contains 80% of the world's known land-based resources. The Nikopol, Chiatura, Tomak Bolshoi (all CIS) and Moanda (Gabon) deposits comprise 5.7%, while Groote Eylandt (Australia) has 2% of the world's Mn resources. An extensive tabulation of Mn deposits and occurrences of the world including tonnages and ore grades has been compiled by Laznicka (1992). Seventy five percent of Mn metal mined is derived from five countries; South Africa, China, Gabon, CIS and Australia.

The concentration of global Mn production and resources is also reflected in the current mining industry, which includes just a few large international companies. Production of high-grade (>44% Mn) ore is mainly by Comilog (Moanda, Gabon) and GEMCO[2] (Groote Eylandt). Medium-grade (40-44%) ore is produced by Samancor (KMF), Assmang (KMF) and CVRD (Urucum, Brazil). Low-grade (<40% Mn) ore is produced by largely state owned enterprises in China, CIS, and India. In Australia, high-grade Mn ore is produced from the Groote Eylandt (NT) and Woodie Woodie (WA) mines. The average Mn content of ore produced globally during 1999 was about 34% (Jones 2000). Manganese ore prices are quoted in $US per tonne unit of Mn, ie per 1% of contained Mn per tonne of ore or concentrate.

Genetic category	Source of Mn	Lithological association	Examples
A. SEDIMENTARY			
	(1) Non-volcanogenic	(a) Terrigenous-marine	Nikopol, Bolshoi Tomak, Chiatura, Groote Eylandt, Mezhdurechy
		(b) Carbonate-marine	Postmaster district, Molango.
		(c) BIF-related	Kalahari, Otjosondu, Urucum
	(2) Volcanogenic	(a) Greenstone-related	Olympic peninsula, Noda-Tamagawa, Parsetten
		(b) Felsic/intermediate volcanics-related	East Cuba, Langban, Santa Rosalia, Migouden, Atasu
B. SUPERGENE			Woodie Woodie, Nsuta, Moanda, Penganga Group, Amapa
C. HYDROTHERMAL			Philipsberg, Lake Valley

Table 9. Classification of land-based manganese deposits (modified from Roy 1981)

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[2] Wholly owned by Samancor.

Country	Mn (metal) resource (Mt)	Mn (metal) production 1999 (Mt)	Av ore grade 1999 (% Mn)
South Africa	4000	1.3	43
CIS	520	0.9	31
Brazil	51	0.6	39
Australia	90	0.9	49
China	100	1.1	20
Gabon	160	1.0	46
India	50	0.6	38
Mexico	9	0.2	37
Ghana	1	0.2	32
Other	20	0.2	30
TOTAL	5000	7.0	34

Table 10. Countries with significant manganese resources and production (source: Jones 2000, 2001)

Exploration and evaluation

The most promising exploration targets are sediment-hosted deposits, in particular, Proterozoic to Tertiary sedimentary units containing passive continental margin, shallow marine sequences. Studies of global Mn accumulation over geological time have suggested four depositional peaks in the Palaeoproterozoic, Jurassic, Oligocene and Pliocene-Quaternary. There is also a direct to indirect spatial coincidence with mafic rocks (particularly basalt) that act as a crustal store and are therefore a potential metal source when subjected to leaching processes (Laznicka 1992).

An exploration strategy similar to that for iron ore is employed for manganese. Economic manganese deposits are relatively large in bulk tonnage (30-300 Mt) and are at or near the surface, like iron ore, making them exploration targets of significant areal extent. Remote sensing methods such as satellite imagery, airborne geophysics and hyperspectral mapping can be used at a regional level.

Satellite imagery

Satellite imagery covers large areas and can be used to map outcropping or subcropping manganiferous zones and related vegetation types.

Airborne geophysics

Airborne geophysics is cost effective in locating flat-lying Mn oxide sheets at shallow depths in relatively resistant host rocks (Irvine and Berents 2001). Airborne electromagnetic (AEM) methods are able to detect manganese oxides when present in moderate amounts due to their conductive properties. Results from a Geotem AEM survey flown at 600-1000 m line spacing over the Groote Eylandt deposits outlined conductive areas that correlated well with defined manganese ore zones (Figure 37). This Geotem AEM method has also been successfully used to locate subsurface manganese mineralisation on the mainland south of Groote Eylandt (Berents *et al* 1994) and in the Bootu Creek area to the north of Tennant Creek (Nunn 1997).

Hyperspectral mapping

Hyperspectral ground reflectance data can be collected from a conventional airborne geophysical platform

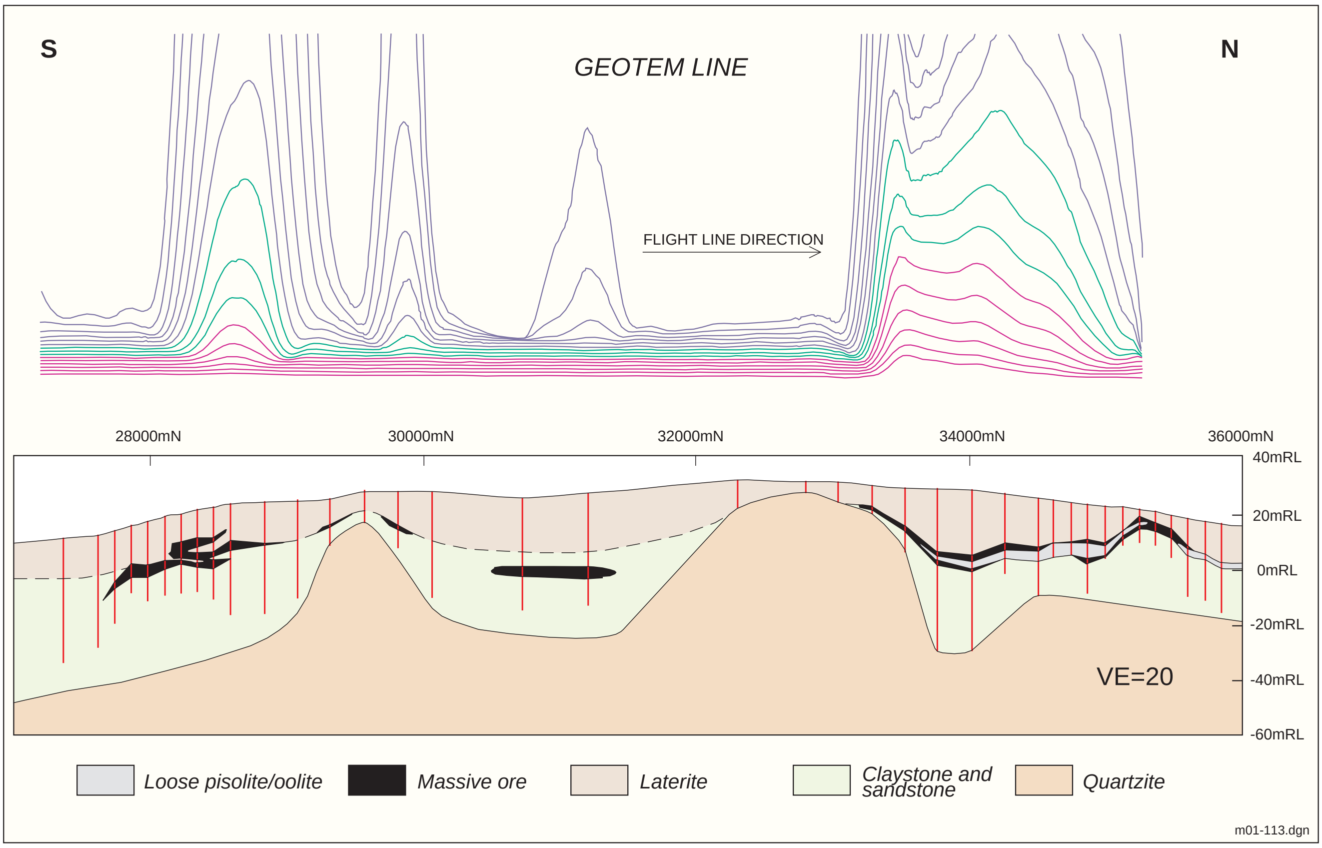

Figure 37. Geotem airborne electromagnetic response over Groote Eylandt Mn deposits (modified from Irvine and Berents 2001)

(Hausknecht *et al* 2000) or satellite (eg JERS and ASTER). Commercial airborne sensors include OARS (Operational Airborne Research Spectrometer), HYMAP, GEOSCAN and AMS (Airborne Multispectral Scanner). Hyperspectral mapping allows the identification of most species of phyllosilicates, clays, carbonates and metal oxides that occur in regolith and parent rocks. Manganese oxides have a distinctive low reflectance signature relative to clay and iron oxide minerals (see **Figures 12**, **57**). Spectra of four manganese minerals are shown in **Figure 38**.

Regional reconnaissance work is followed up by systematic sampling of natural or near surface (via costeaning) exposures. Ground-based electromagnetic (Nunn 1997) and gravity (Dentith *et al* 1994, p 70, Consolidated Minerals 2000) geophysical surveys can be used to gain a better understanding of the shape, size, depth and orientation of subsurface deposits. Due to the hardness of Mn oxide minerals and the necessity to sample material below the water table, reverse circulation (RC) drilling is preferred over percussion and RAB. Reconnaissance drilling may start on a square grid, spaced at 400 m (eg Berents 1994), 240 m (eg Groote Eylandt) or 100 m (eg Woodie Woodie), depending on: 1) understanding of the geological model; 2) cost factors; and 3) the exploration strategy of the company.

Once the presence of an economic deposit has been established, the spacing of drillholes can be reduced to 120 m or 50 m for resource estimation, then to 60 m or 25 m (or less) for ore reserve and mine planning, depending on the orebody size and variations in the quality of the deposit. Sampling intervals for drillhole material can be 0.5 to 1 m depending on the average thickness of the ore zone. Drill material is normally split, with half being sent for chemical analysis for the following constituents: total Mn, total Fe, SiO_2, Al_2O_3, P_2O_5, BaO, K_2O, Na_2O, MgO, CaO, SrO, C, S, H_2O, TiO_2, Pb, Zn, Ni, Cu, Co and As. Once the main impurities in the Mn deposit are known, the list of analysed elements can be substantially reduced.

A variety of chemical techniques are available for the analysis of samples, including X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), Atomic Absorption Spectrometry (AAS) and Inductively Coupled Plasma Spectroscopy (ICP). XRF, AAS and ICP methods will give the elemental constituents of the ore, whereas XRD can provide information on mineralogical composition. Before samples are sent for analysis, wet screening of the material can be carried out to replicate the grade of beneficiated Mn ore. This technique is used by GEMCO at Groote Eylandt, in order to reduce the clay content in the matrix of pisolitic ores.

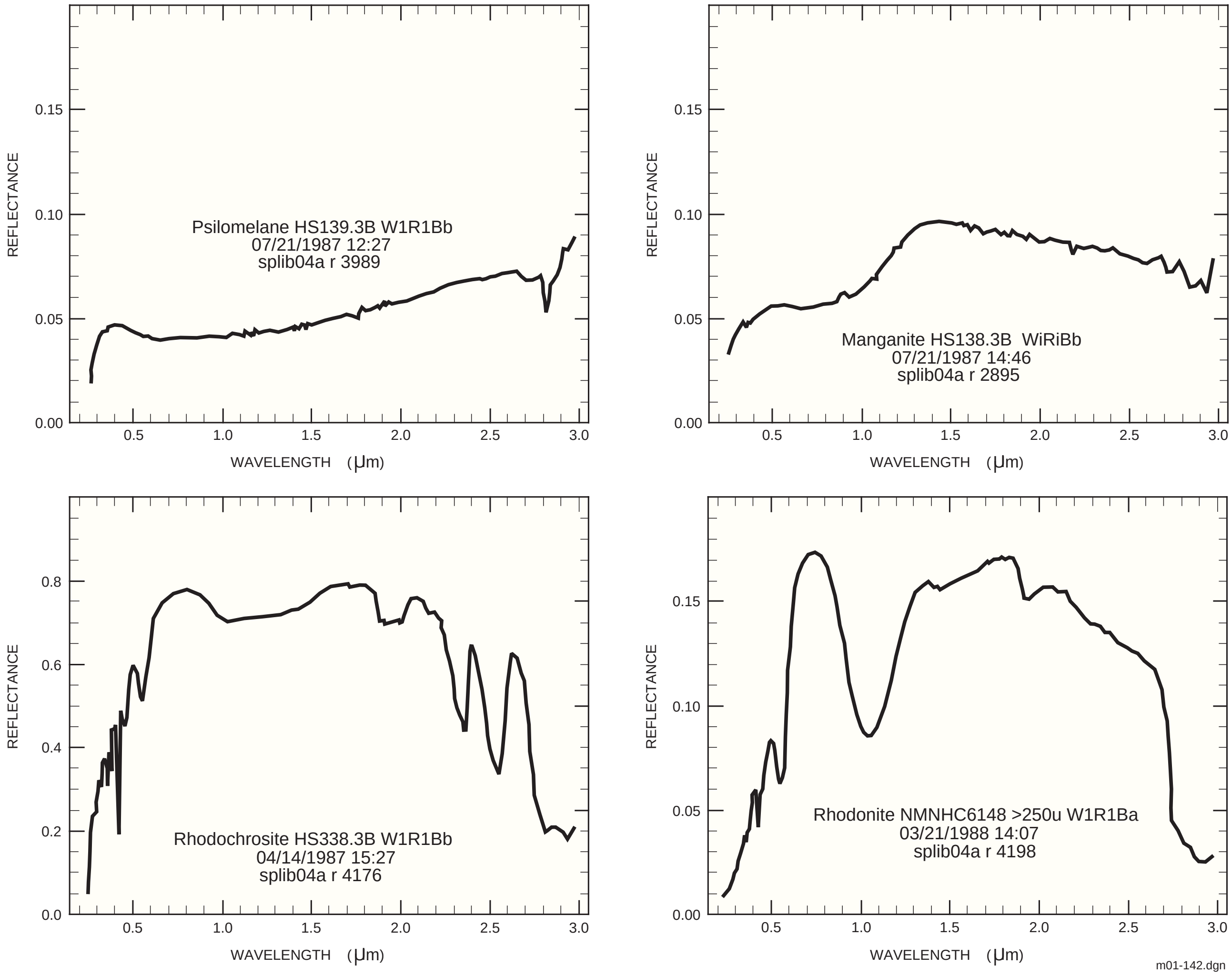

Figure 38. Spectra of some manganese ore minerals, from USGS digital spectral library (after Clarke *et al* 1993)

Tonnages, grade and mineralogy, associated impurities, the amenability of the ore to beneficiation and transport costs are all important factors in assessing the economic potential of a manganese deposit. Manganese ore specifications vary depending on its intended commercial application, whether it be for metallurgical purposes (eg ferromanganese or silicomanganese alloys in steel-making) or for chemical products and applications (eg electrolytic manganese dioxide (EMD) in alkaline batteries).

Metallurgical and industrial uses

Metallurgical grade

About 95% of all manganese ore produced is converted to ferromanganese and silicomanganese for the iron and steel industry. Minor amounts are used to produce manganese metal, duralumin (strengthened aluminium) and manganese bronze. High-carbon ferromanganese is produced in electrical or blast furnaces from Mn ore containing >40% Mn, an Mn to Fe ratio of at least 7:1, <10% SiO_2 and <0.2% P (Cairncross *et al* 1997). Chemical specifications for ferromanganese categories are given in **Table 11**. Production of the alloy was 3.66 Mt in 1999 (Jones 2000). Low-carbon ferromanganese is essential for the production of low-carbon heat-resistant steel and is normally produced by the reduction of manganese ore with silicomanganese in an electric arc furnace.

Silicomanganese is produced in an arc furnace from ore containing lower Mn grades (30-40%), and higher levels of SiO_2. Chemical specifications for silicomanganese are given in **Table 11**. Production of the alloy was 2.9 Mt in 1999 (Jones 2000).

Manganese is also used in low-alloy steel for constructional purposes and in heavy-duty cast iron. Rail steel for example requires high tensile strength and commonly contains 0.9-1.2% Mn (Sully 1987). Certain wear-resistant steels contain 12-14% Mn (Cairncross *et al* 1997). Production of manganese metal (97-98% Mn) is via reduction with aluminium from high-grade Mn ore that has a very low iron content.

Chemical grade

About 5% of manganese ore is used in a wide variety of products and applications including the manufacture of batteries, as a drying agent or catalyst in paints and varnishes, as a decolouriser in glass manufacture, as a trace element in fertilisers and animal feed and in special chemicals. These require primarily high-grade material (48-52% Mn). The manufacture of alkaline dry cell batteries consumes about 145 000 t/yr or 40% of global chemical-grade Mn production. Naturally occurring manganese dioxide (NMD) and synthetically produced manganese dioxide (SMD) are used. Chemical processing (CMD) or electrolysis of manganese sulfate (EMD) can both produce SMD, but the latter method is more common.

Ore extraction and treatment - a summary

Mining of manganese ore is generally carried out by large operations using surface methods (open pit) that extract 0.2-2 Mt/yr. However, underground mining is conducted in the Kalahari Manganese Field, where premium-grade (50-60% Mn) Wessel-type ore is obtained. The mining operation on Groote Eylandt is representative of opencut manganese mining worldwide and the following account is based on a detailed description by Turnbull (1993).

The first step in the mining sequence involves the clearing of scrub and trees on the planned mining blocks using D9 bulldozers. Topsoil is removed using Caterpillar scrapers and spread on areas of backfill that have been prepared for rehabilitation. Crawler-track-mounted drill rigs are used for blast hole drilling in the overburden and ore. Drillhole patterns are dice-5 and are normally spaced at 8x7 m in ore and 16x7 m in overburden. Blasted overburden is removed by 17 m^3 bucket excavators into 136 t rear dump trucks that haul the material to adjacent mined quarries. Blasted ore is loaded by 9 m^3 excavators into 136 t rear dump trucks and hauled to run-of-mine stockpiles.

Manganese ore is mined from up to nine different quarries to meet GEMCO's customer product requirements. Mining blocks are 75 m wide and 200 m long. Quarries are located between 2-10 km from 22 stockpiles that are maintained near the primary crusher to allow simultaneous blending of ore and to maintain a consistent quality product. The ore to waste ratio for the remaining resource is 1:2.2 (D Mallon, GEMCO, pers comm 2000). For comparison, mining at Woodie Woodie in Western Australia is via small open cuts with a general ore to waste ratio of 1:5. Dewatering of the quarries by submersible pumps is important due to the low-lying nature of the orebody. About 30 ha of lease area is cleared, due to the advance of mining each year, but the same area is rehabilitated behind the active quarries.

Run-of-mine ore is crushed to -150 mm material at the primary crusher, which has a capacity of 1000 t/h. This material is then beneficiated and upgraded in the concentrator plant by heavy medium separation. The concentrator consists of five sections; primary crushing station, feed preparation, drum scrubbing, heavy medium drum for upgrading lump ore and heavy medium cyclones for upgrading fines (Christison 1993). Two basic types of manganese products are produced; Lump ore (-75 to +6.7 mm in size) and Fine ore (-6.7 to +0.5 mm in size). These two categories can be further divided into premium, metallurgical and siliceous grades as shown in **Table 12**. Product

Mn alloys	Mn (%)	Si (max %)	C (max %)	P (max %)	S (max %)
High-carbon ferromanganese	74-82	1.2	7.5	0.35	0.05
Medium-carbon ferromanganese	80-85	0.35-1.0	1.5	0.3	0.02
Low-carbon ferromanganese	85-90	2.0-7.0	0.75	0.2-0.3	0.02
Silicomanganese	65-68	13-21	1.5-3.0	0.2	0.04

Table 11. Specifications for ferromanganese and silicomanganese (modified from Holmes 1994)

Manganese products		Mn (%)	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	P (%)	Sizing (mm)
Groote Eylandt Lump	Premium	51-53	2.5-3.5	3.5-4.5	3-4	0.07-0.10	-75 to +6.7
	Metallurgical	48-50	3-4	5.5-7.5	4-5.5	0.07-0.10	-75 to +6.7
	Siliceous	40-42	4-7	13-16	4-7	0.07-0.10	-75 to +6.7
Groote Eylandt Fines	Premium	51-53	2.5-4	3.5-4.5	3-4	0.07-0.10	-6.7 to +0.5
	Metallurgical	48-50	3-4	5.5-7.5	4-5.5	0.07-0.10	-6.7 to +0.5
Woodie Woodie Lump	Metallurgical	48-50	4-5	11-13	0.5-1.0	0.02-0.05	-75 to +6.5
Woodie Woodie Fines	Metallurgical	44-46	4-6	10-13	0.5-1.0	0.02-0.06	-6.5 (90%)

Table 12. Mn products from Groote Eylandt (NT) and Woodie Woodie (WA) mines

specifications of the Woodie Woodie operation in the Pilbara region of WA are also shown for comparison.

MANGANESE DEPOSITS OF THE NT

Manganese exploration and mining in the NT

Manganese mineralisation was first discovered on a beach near Alyangula on *Groote Eylandt* during a geological reconnaissance by HYL Brown in 1907 (Brown 1908). The discovery was not followed up until 1960, when PR Dunn collected high-grade (>50% Mn) manganiferous material during a regional mapping program. Further exploration by the BMR in 1961 identified three significant high-grade manganese occurrences in the vicinity of the Groote Eylandt Mission (Crohn 1962).

In 1962, a BHP Ltd geologist, WC Smith, investigated the occurrences and concluded that there was sufficient potential resource to warrant a thorough evaluation of the deposits. After further investigations, BHP formed the Groote Eylandt Mining Company (GEMCO) and opencut mining commenced in 1966. Samancor Ltd subsequently acquired BHP's interests in GEMCO in December 1998. Mn ore production peaked at 2.2 million tonnes in 1990 and the operation currently (00/01) produces 1.6 Mt/y of high-grade manganese product (49% Mn) from 2.8 Mt of ore mined. This represents about 10% of the world supply of manganese ore for various metallurgical and chemical uses, and makes GEMCO the third biggest producer of manganese in the world. As of January 2001, a remaining total reserve of 94 Mt, which contains a recoverable manganese product of 40 Mt grading 48% Mn, 7.4% SiO$_2$, 0.09% P and 4.7% Fe, will provide a mine life of 26 years at current mining rates (D Mallon, GEMCO, pers comm 2001).

In 1952, exploration for manganese in the Calvert Hills area (see **Figure 9**) led to the discovery of manganiferous outcrops that became known as *Camp 1* (Murray 1953). Several other nearby occurrences were also discovered and assessed, but no development work was undertaken.

In 1954, the mining and treatment of uranium at Rum Jungle to the south of Darwin generated a demand for MnO$_2$ that led to the development of a small unconformity-related deposit (*McLean's*) near Mount Shoobridge (see **Figure 5**). About 540 t of handpicked ore grading 60% MnO$_2$ was mined and trucked to Rum Jungle between 1954 and 1964.

Deposits at *Mucketty*, near Helen Springs to the north of Tennant Creek, were also developed to supply the Rum Jungle operation. Mining from five shallow open cuts during the period 1955-1969 produced 13 280 t of Mn ore grading 66% MnO$_2$. Drilling by the BMR indicated that manganese ore beneath the open cuts diminishes in both grade and thickness below a depth of 10 m (MacKay 1956). Production from the Mucketty mine ceased in 1969 when the Rum Jungle treatment plant completed the processing of uranium ores from the Rum Jungle Creek South mine. Exploratory drilling by BHP Ltd on deposits further to the east indicated that metal-grade manganese mineralisation continues to at least 80 m depth (Nunn 1997).

Following the delineation of minable iron ore resources at Frances Creek, several iron-manganese gossans (eg *Lewis* and *Millers*) in the northern part of the iron field were investigated between 1965 and 1977. Drilling and surface sampling indicated that the gossans were relatively low in manganese (7-17% Mn) and high in iron (Shields 1966, Friesen 1972, Newton 1977).

Sporadic exploration over the western and southern margins of the Carpentaria Basin on the mainland has been conducted by various companies since 1964 (eg BHP 1964a, Chesnut *et al* 1967, Still 1971, Lockhardt 1977, Paterson 1997). A number of significant prospects (eg South Rosie Creek and Batten Creek) have been discovered in this region using the Groote Eylandt Mn model. *South Rosie Creek* is the largest of these occurrences and contains 4.5-5.5 Mt @ 25% Mn (Berents 1994).

Total production of manganese ore from the Northern Territory is about 50 Mt and is dominated by the Groote Eylandt operation (**Figure 39**). A tabulation of manganese occurrences and resource estimations is presented in **Appendix 2**.

Classification of the manganese deposits of the Northern Territory

For the purposes of this publication the manganese deposits of the Northern Territory can be divided into three types:

- Sedimentary (stratiform), eg Groote Eylandt;
- Hydrothermally concentrated (low temperature replacement), eg Bootu Creek; and
- Surficial, eg Calvert Hills-Robinson River area.

Sedimentary deposits.

These are stratiform and are hosted in marine terrigenous clastic sediments. The well documented world class *Groote Eylandt* deposit is the holotype. This deposit and several other prospects in the Carpentaria Basin are confined to shallow

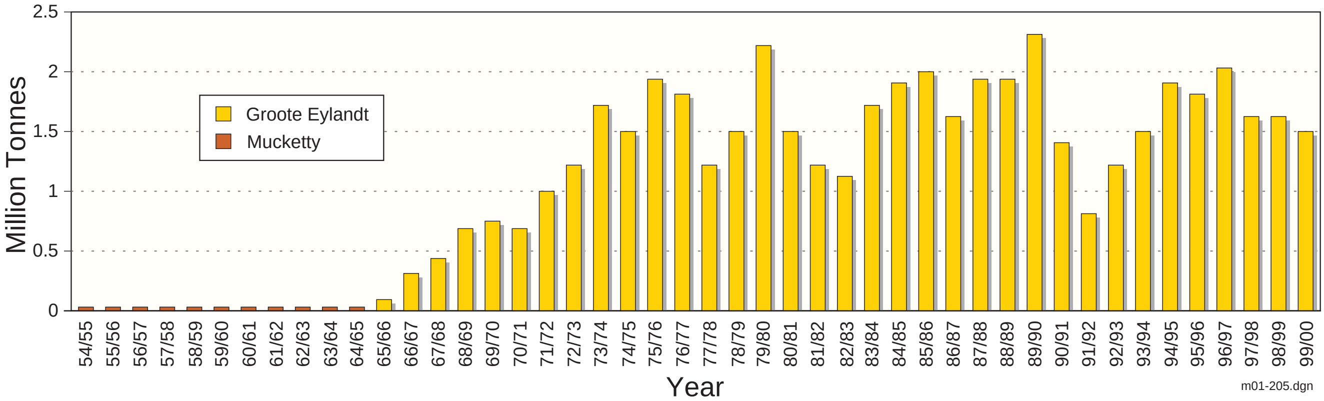

Figure 39. Past production of manganese ore in the Northern Territory

marine Cretaceous sediments, which are adjacent to Proterozoic terraces that define a Late Albian (ca 100 Ma) shoreline. Mineralisation ranges from disseminated Mn oxides in clayey quartz arenite to massive bedded pisolitic ore up to 11 m in thickness.

Proterozoic sedimentary basins in the NT lack significant BIF units and extensive Mn-rich carbonates, and this reduces the potential, respectively, for BIF related (Kalahari-type) and carbonate hosted (Molango-type) Mn deposits.

Hydrothermal deposits

These are low temperature epigenetic deposits that form stratabound massive Mn (± Fe) oxide lenses in shallow marine sediments. The Mucketty and Bootu Creek deposits, to the north of Tennant Creek, are examples of this style of Mn mineralisation. Cryptomelane is the dominant ore mineral; pyrolusite and minor hollandite are also present as are varying amounts of quartz and goethite. Minor barite, calcite and chalcedony occur in the gangue suite. Anomalous trace element levels (eg 1000 ppm Cu and 900 ppm Pb) are also characteristic. Mn (± Fe) oxides replace quartz arenite, siltstone and dolomite and form lenses up to 12 m in thickness. Massive ore is confined to replaced siltstone and dolomite lithologies.

These deposits are not proximal to volcanic or plutonic rock types like many of the deposits described in Roy (1981) and can be viewed as being distal. They are related to shallow regional hydrothermal activity that has remobilised Mn from sediments and volcanics elsewhere in the sequence.

Surficial deposits

Surficial deposits of Mn oxide are small in tonnage and are related to manganiferous carbonate sediments, unconformities, laterite development, or a combination of two or more of the above. Ore grades can be reasonable but are usually patchy in distribution. Occurrences in the Calvert Hills area (McArthur Basin) are examples of manganiferous carbonate-related deposits; occurrences in the McLeans-Green Ant Creek area (Pine Creek Orogen) are examples of unconformity-related deposits; East Arnhem Land occurrences are examples of laterite-related Mn deposits.

Sedimentary deposits

Fourteen sedimentary manganese occurrences within the Northern Territory have been recorded in open file reports. Most of these are along the western margin of the Carpentaria Basin. Six deposits (A, D, F, H, J and K) have been recognised on Groote Eylandt, although numerous other occurrences have been recorded in closed file reports. Mainland occurrences are scattered across ARNHEM BAY and MOUNT YOUNG.

Carpentaria Basin

Groote Eylandt

The Groote Eylandt deposits are situated along the western coastal plain of the island, which is 640 km to the east-southeast of Darwin. They comprise three large sheet-type orebodies (**Figure 40**) that cover an area of 75 km^2. The Groote Eylandt Mining Company Ltd (GEMCO) manages the mining and processing operation and is a wholly owned subsidiary of Samancor Ltd (60% BHP-Billiton, 40% Anglo American Corp). Mining of the deposits commenced in 1965 and about 90 Mt of ore has been mined to produce 50 Mt of manganese product (Lump and Fine ore) to the end of June 2001. A description of the Groote Eylandt mining process is given in the preceding section.

Exploration and Development

In 1960, the collection of four high-grade (>50% Mn) samples from a site near quarry A by PR Dunn triggered follow up mapping and test pit work by the BMR. This work identified three significant deposits (A, E and D) of high-grade manganese between the Angurugu and Emerald rivers (Crohn 1962). BHP Ltd investigated these deposits (Smith 1962), and between 1963 and 1967, completed 1500 rotary and percussion drillholes (totalling 19 800 m) and 700 to 800 test pits. A “reserve” of 64 Mt grading 30-50% Mn was estimated (GEMCO 1967).

Reconnaissance manganese exploration across the entire island identified 43 occurrences that were examined by 129 prospecting drillholes (Read 1964). This work indicated that disseminated manganese in Cretaceous sediments along the western portion of Groote Eylandt is widespread and that economic deposits occur in the vicinity of Angurugu. Gravity survey work, which totalled 314 line km at a station spacing of 60 m, was used to extrapolate ore zones between widely spaced drillholes (Bolton *et al* 1990).

GEMCO, then a wholly owned subsidiary of BHP, was formed in 1964. It initially mined Mn ore from Quarry F in 1965, before full-scale mining (from Quarries A, F and G)

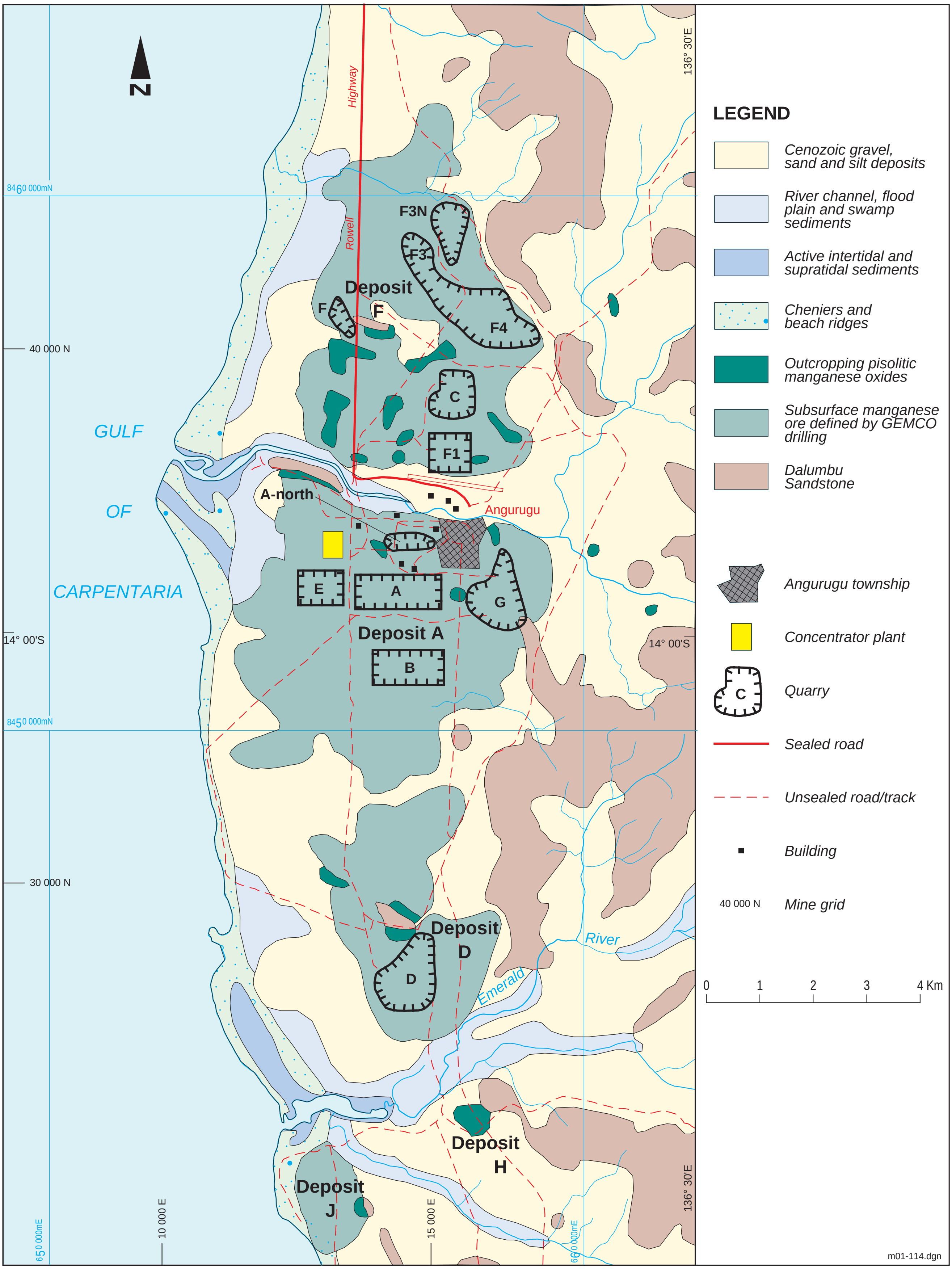

Figure 40. Location of Mn quarries on Groote Eylandt (modified from GEMCO location plan, April 1997)

and shipment of ore commenced in 1966. Construction of a permanent 1 Mt/yr crushing and screening plant to the south of the Angurugu River was completed in 1972. This treatment plant was upgraded in 1986-87 to a capacity of 2.3 Mt/yr. Mining has been undertaken from 11 quarries located on Deposits F, A and D (Figure 40).

Resource assessment and development on Groote Eylandt usually involves up to three stages of RC drilling (Bolton *et al* 1990). Initial drilling is on a 240 m-spaced grid. This is then infilled by 120 m-spaced holes, once significant manganese mineralisation is encountered. Ore reserves are commonly calculated after this stage of drilling. Hole spacing is reduced to 60 m should further information for reserve estimation and/or mining be required. Drillhole samples containing Mn mineralisation are collected every 0.5 m, wet screened at 0.5 mm mesh and assayed on site at the GEMCO laboratory using XRF and AAS techniques.

Resource modelling and estimations by GEMCO use a 40% Mn cut off grade, a minimum ore thickness of 1.0 m and a specific gravity for the ore of between 2.4 and 3.0, depending on the ore type. An orebody block model has been created using a parent cell size of 30x30x1 m and lithological and assay data from about 4500 drillholes. Cross-sections and 3D orebody models of the mining horizons can then be generated using VULCAN software. Using these methods, a Total Resource of 212 Mt grading 47.5% Mn, 8.5% SiO_2, 0.09% P and 4.6% Fe with a strip ratio of 2.18 has been estimated. Quoted grades represent the marketable product, not bulk *in situ* grades. The contained manganese product within the resource is about 88 Mt.

Geological Setting

Unless otherwise indicated, the following geological descriptions are largely derived from Pietsch *et al* (1997). Groote Eylandt occupies the northeastern portion of the Proterozoic McArthur Basin and western margin of the Mesozoic Carpentaria Basin (**Figure 11**). Basement Palaeoproterozoic granite and metamorphics, which form part of the Arnhem Inlier, outcrop on islands to the northwest and have been intersected in drillholes near Alyangula on Groote Eylandt (Slee 1980). Well jointed, coarse, cross-bedded quartz arenite of the Palaeoproterozoic Dalumbu Sandstone dominates rock outcrops on the island (**Figure 41**).

Thickly bedded pebbly quartz arenite of the Dalumbu Sandstone forms rugged, sparsely vegetated hills and scarps. It is 500-1000 m thick on Groote Eylandt and dips gently (1-2º) to the south. A thin (up to 15 m thick) ferruginised basalt interval has been mapped near the base of the sandstone. Poorly outcropping Bartalumba Basalt conformably underlies the Dalumbu Sandstone. This volcanic unit consists of 200-400 m of vesicular and amygdaloidal basalt and microdiorite. This, in turn, overlies a sequence of pebbly quartz sandstone (Alyinga Sandstone) and pebbly lithic sandstone and quartz arenite (Milyema Formation), both of which outcrop in northern Groote Eylandt.

Early to Middle Cretaceous sediments were deposited unconformably over a deeply dissected and undulating surface that formed on Palaeoproterozoic quartz sandstone and basalt. The Cretaceous sediments are up to 100 m thick (Water Bore RN 22222 at Angurugu) and are assigned to the Walker River Formation (Krassay 1994b). They are poorly exposed on the island, so most information about them has been obtained from mineral exploration and water bore drilling. K/Ar dating of glauconite grains from claystone beds beneath the manganese horizon indicates an age of 95 Ma and this is consistent with palaeontology-based estimates (Pracejus 1989). The Walker River Formation dips gently to the west and southwest in the mine areas.

Drilling by GEMCO has identified two discrete sub-basins on the western coast of Groote Eylandt (**Figure 41**). The northern sub-basin consists of locally derived, unfossiliferous quartz sandstone, conformably overlain by shallow marine glauconitic claystone, the upper portion of which hosts the primary pisolitic manganese horizon (**Figure 41**). In the southern sub-basin, a manganiferous sandy calcareous siltstone (marl) containing rhodochrosite and manganocalcite underlies manganese oxide-cemented sandstone (Bolton *et al* 1990). Manganiferous marl has also been intersected at depth in an area about 8 km to the south of Alyangula (Slee 1980).

In the central part of Groote Eylandt, flat-lying sandstone and claystone infill palaeovalleys in the Dalumbu Sandstone up to 100 m ASL. Multicoloured, mottled claystone, siltstone and minor sandstone are exposed and have been intersected in numerous water bores over northern areas of the island (Karp 1992). Large, laterally discontinuous bodies of Late Cretaceous to Tertiary conglomerate and claystone are present in places in the mining areas. A channel-fill wedge of claystone with a developed laterite profile is present in the northeastern corner of the F1 quarry and has reduced the thickness of the ore horizon (**Figure 42**). Colluvial and alluvial conglomerate lenses are also found in the northern areas of the deposit in the lower part of the laterite and these generally consist of pebble- to cobble-sized quartz arenite, reworked Mn ores and Fe oxides in a matrix of clayey sand (Pracejus 1989).

Tertiary laterite and Quaternary sand and clay cover extensive parts of northern and western Groote Eylandt, respectively. Laterites consist of ferruginous to kaolinitic mottled clay and sandy clay, goethite and manganese oxide pisoliths, and dispersed pebbles and clasts of manganese oxide and quartz arenite (Bolton *et al* 1990). Lateritic alteration of the manganese ore horizon is extensive and has produced important secondary supergene products that form a major component of the deposits (Pracejus *et al* 1988).

Orebody character and composition

Previous descriptions of the manganese mineralisation, host rocks and various models on ore genesis have been published by Smith and Gebert (1970), McIntosh *et al* (1975), Slee (1980), Ostwald (1981, 1990), Varentsov (1982), Bolton *et al* (1988, 1990), Pracejus *et al* (1988, 1990) and Pracejus and Bolton (1992). Detailed descriptions of the mineralogy and petrology of the ore and associated sediments are given by Frazer and Belcher (1975), Ostwald (1975, 1980, 1981, 1988) and Ellis (1978). The following description is essentially based on Slee (1980), Pracejus (1989) and Bolton *et al* (1990), on numerous discussions with Dave Mallon (GEMCO resource geologist) and on a field visit to the area in July 1997.

The Groote Eylandt manganese deposit consists of stratiform, massive to disseminated ore in a sheet-like body. It averages 3 m in thickness, and thins and dips gently (<5°) to the west (**Figure 41**). GEMCO recognises four separate deposits (Deposit F, A, D and J) that contain recoverable resources (**Figure 40**). These deposits occupy a series of west-northwest-trending depressions between elongate ridges of Dalumbu Sandstone (**Figure 43**) and together they form an ore zone 22 km long and up to 6 km wide. This orebody varies

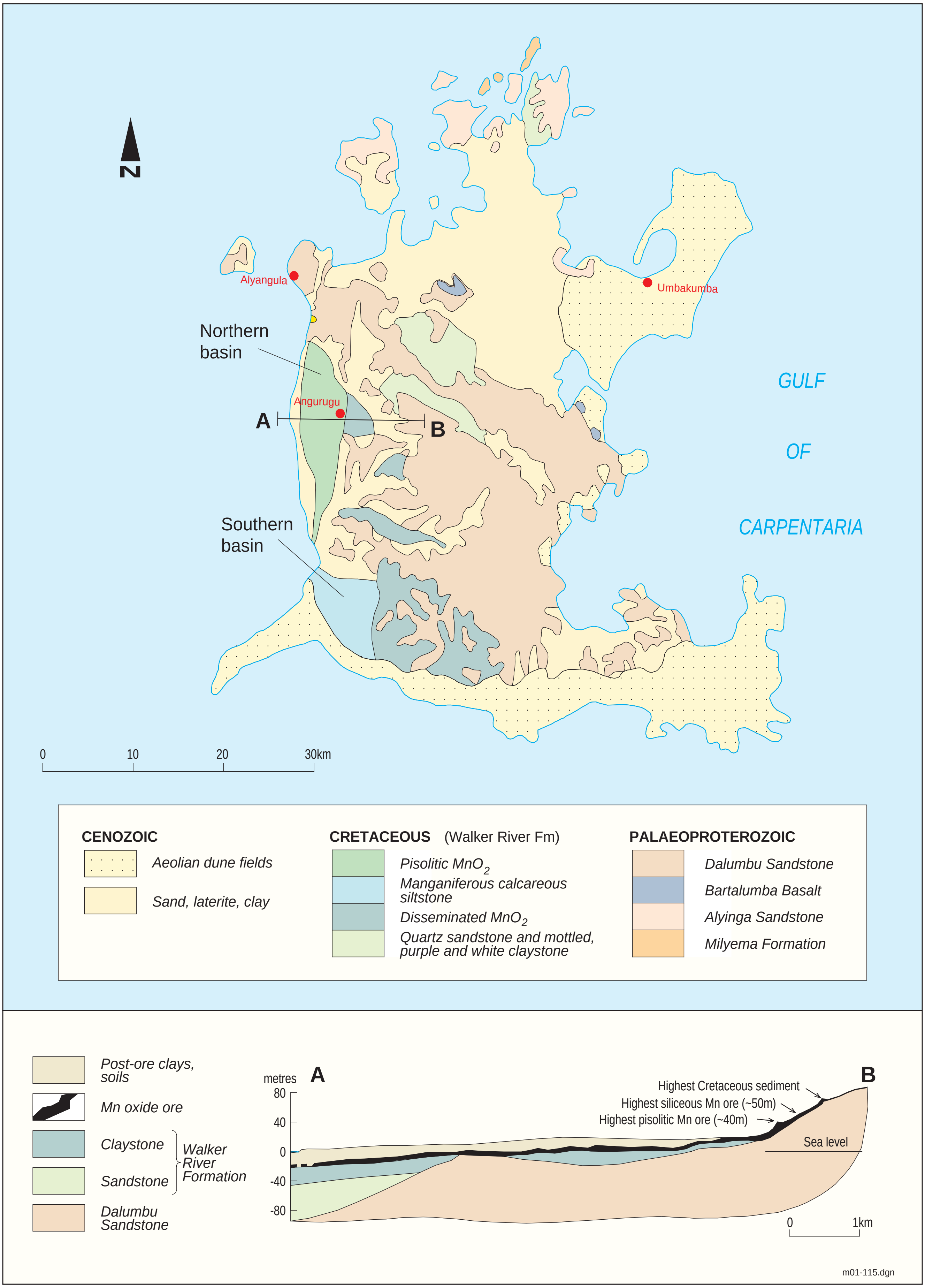

Figure 41. Simplified geology of Groote Eylandt (modified from Bolton *et al* 1990)

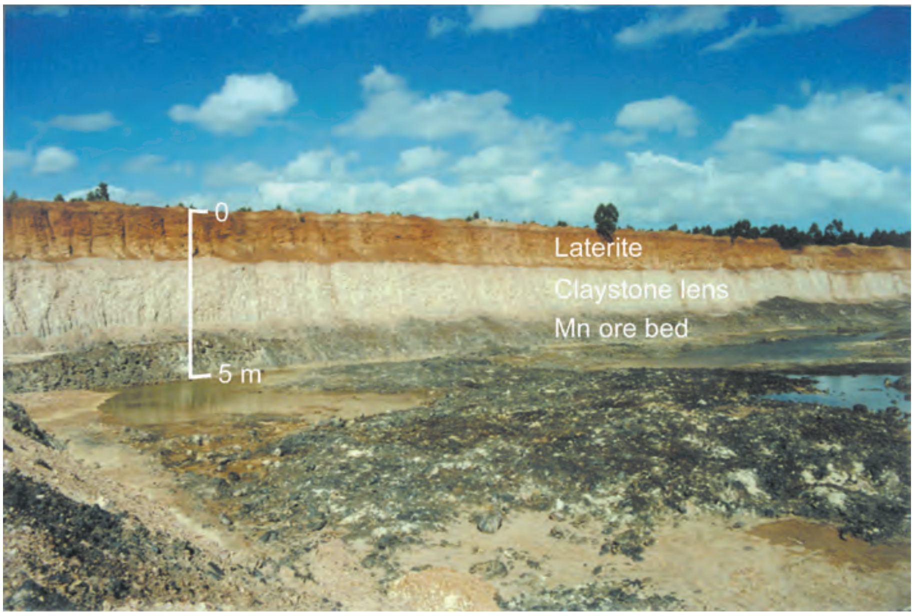

Figure 42. Wedge-shaped claystone lens along northern wall of Quarry F1, Groote Eylandt

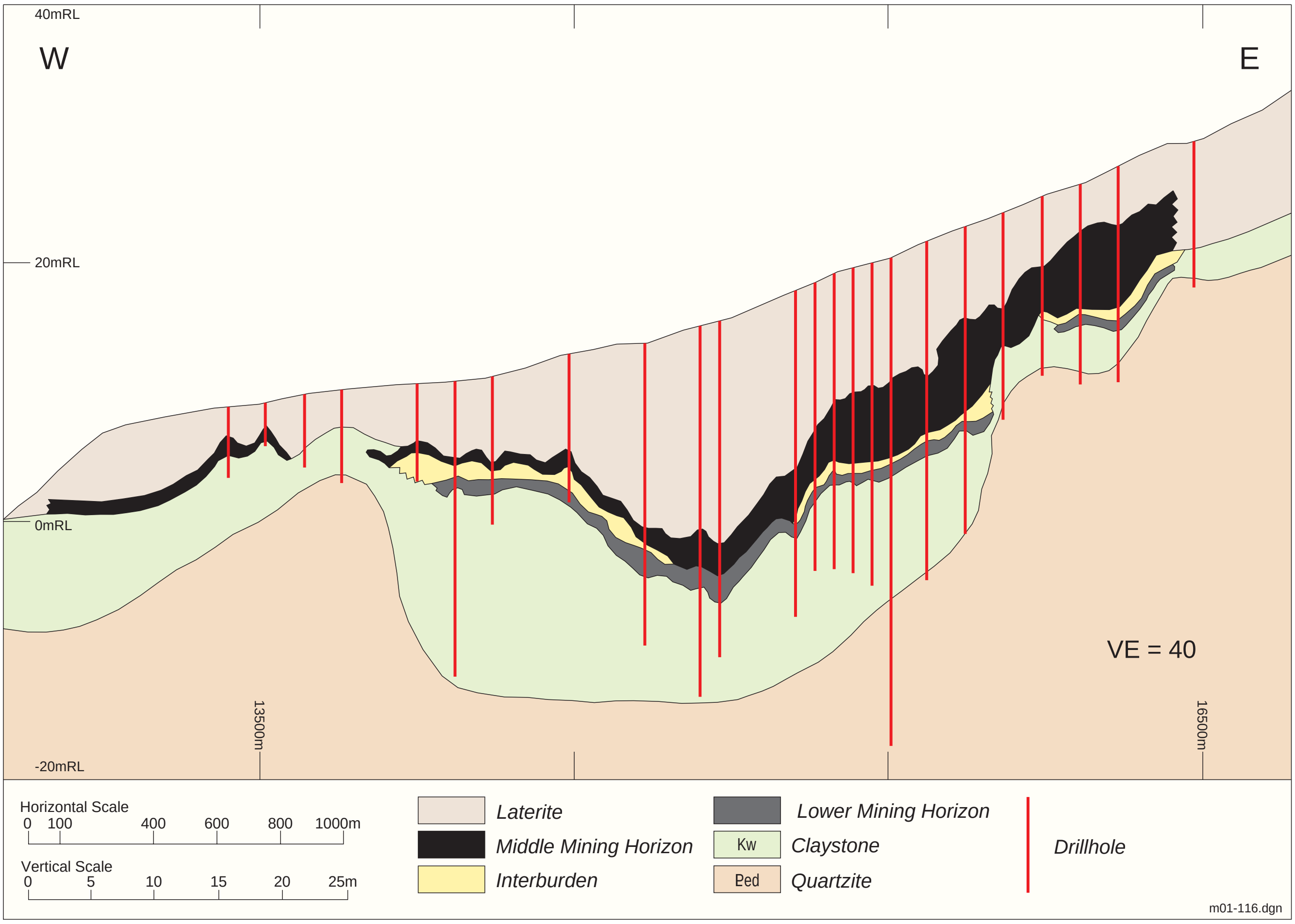

Figure 43. Cross section along 40960mN in Deposit F, Groote Eylandt (modified from BHP 1995)

in thickness from 0.1-11.5 m and occupies an elevation from 50 m above to 50 m below MSL. The thickest portions of the ore horizon (>6 m) are confined to discrete pods along the eastern basement terraces. Thinner parts occur over west-northwest-trending basement ridges (**Figure 44**).

Massive manganese oxides outcrop where the ore horizon abuts Dalumbu Sandstone on the eastern side of the deposit and adjacent to basement palaeo-highs. GEMCO has defined ore stratigraphy and recognized three mining horizons, only two of which are currently being worked. These horizons are based on lithology and Mn, Fe and SiO_2 contents (**Figure 45**). The middle mining horizon supplies the bulk of the ore for the mining operation and contains average grades of Mn≥40%, SiO_2<11% and Fe<7%. The lower mining horizon contains

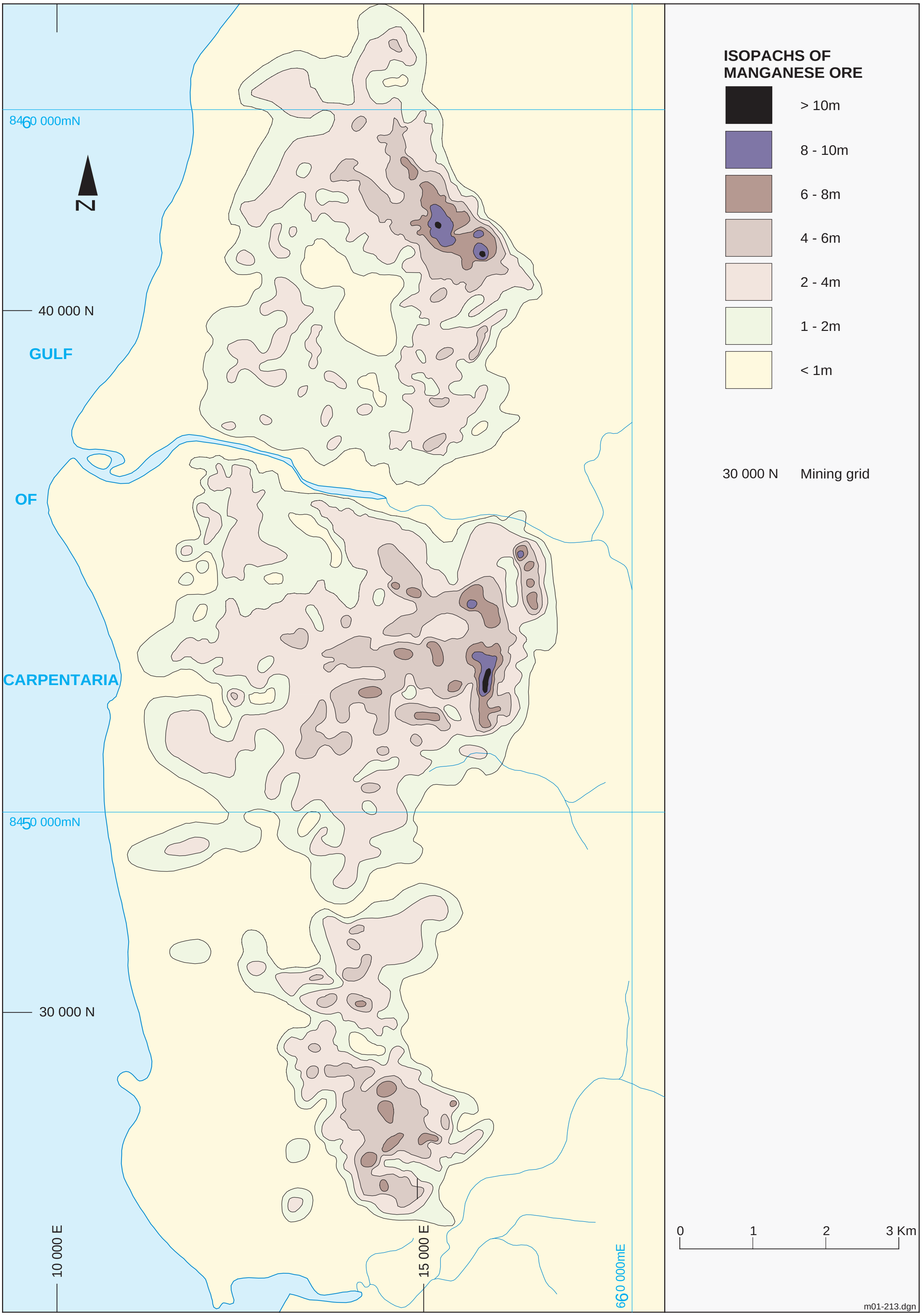

Figure 44. Manganese ore thickness isopachs, Groote Eylandt (data kindly supplied by GEMCO Ltd)

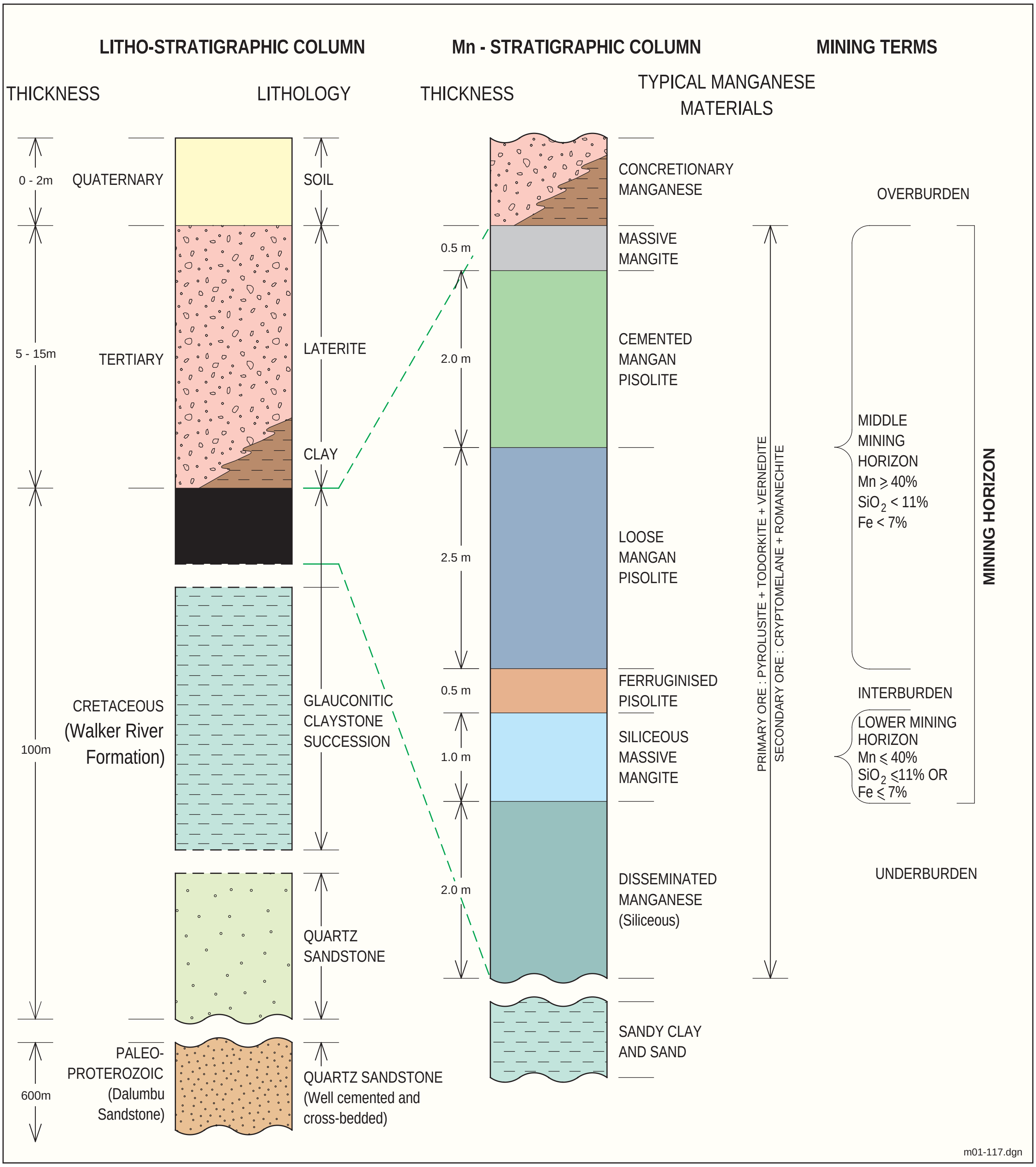

Figure 45. Generalised stratigraphic setting of Groote Eylandt Mn deposits (modified from Bolton *et al* 1990)

ore with average grades of Mn≥40%, SiO_2≥11% or Fe≥7%. The top mining horizon contains concretionary Mn ore that no longer meets Run-of-Mine specifications. A number of manganese ore types are recognised, based on texture, ore/gangue ratio, grade attributes, mineralogy, degree of cementation and lateritisation (see Tables 1 and 2 in Pracejus *et al* 1988).

Widespread, variable, post-depositional, diagenetic supergene and pedogenic processes have produced a complex vertical and lateral distribution of Mn ore units or facies (Pracejus *et al* 1988). Primary sedimentary structures in the massive Mn ore are preserved and are well documented in quarry G (Bolton *et al* 1988). Inversely graded beds are prominent in the lower part of the ore horizon and contain pisoliths grading uniformly from 2-20 mm in diameter over the thickness of the bed (**Figure 46**). Individual beds have been traced for up to 500 m along strike. Normally graded oolitic beds are present higher in the horizon, together with trough cross-bedding, ripple marks and burrow structures.

Figure 46. Inversely graded Mn ore bed at Quarry G, Groote Eylandt (hammer length is 0.4 m)

Petrological and scanning electron microprobe studies indicate that most pisoliths and ooliths do not contain distinct nuclei. When present, nuclei may include silt- to fine sand-sized quartz grains, abraded pisolith or oolith fragments, or aggregates of detrital quartz and clay material. The cortex is accretionary in nature and consists of alternating laminae of romanechite (often altered to cryptomelane) and pyrolusite. Ostwald (1990) identified filamentous and coccoid bodies, wavy and wrinkled lamination (oncolite microstructures), and columnar structures (stromatolites), all of which suggest a biogenic origin for the pisoliths and ooliths. Physical reworking is indicated by the presence of flattened or irregularly shaped grains, and by fractured pisolith and oolith fragments. Pisolitic facies ore is generally best developed on palaeo-seafloor terraces adjacent to palaeo-highs.

Post-depositional textures and structures that have resulted from diagenesis and supergene reworking were described in detail by Pracejus *et al* (1988) and include massive textureless ores, leached ores, siliceous ores, Mn-concretions, Mn-spherulites, Mn-impregnations/cements, replaced ooliths and pisoliths (eg ferruginised), mangcrete and clay pipe structures. Loose mangan pisolite (poorly cemented pisolitic and oolitic ore) is thought to represent the primary ore sediment, whereas cemented mangan pisolite ore is the result of diagenetic processes (Ostwald 1988). Slee (1980) noted sand dykes and pipes at A-west and D quarries, where Cretaceous sand has been injected up to 3 m into the overlying ore.

The ore mineralogy of the deposit is complex and some 13 Mn-oxide minerals have been described (Ostwald 1988). Pyrolusite (MnO_2) and cryptomelane [$(K,Mn)_8O_{16}$] are the dominant mineral phases. Pyrolusite is the main mineral in pisoliths, and also occurs as a cementing medium for pisoliths and as a fine powder (wad) in clay. Cryptomelane is present in pisoliths, dense siliceous ores and as Mn-concretions. Other manganese minerals present to a minor extent are todorokite [$(Mn,Ca,Mg)Mn_3O_7.H_2O$], romanechite [$(Ba,K)Mn.Mn_8O_{16}(OH)_4$], which is a variety of psilomelane, vernadite [$MnO_2.(BaO,Fe_2O_3,Al_2O_3).H_2O$], manganite [gMnOOH], hollandite [$Ba_2Mn_8(O_{16}OH).nH_2O$], nsutite [$Mn(O,OH)_2$], manjiroite [$(Na,Ca,K,Ba)\ (Mn,Fe,Al,Mg)O_{16}.H_2O$], braunite ($3Mn_2O_3.MnSiO_3$), lithiophorite [$(Al,Li)MnO_2(OH)_2$], birnessite [$(Na,Ca)\ Mn_7O_{14}.3H_2O$] and chalcophenite [$(Zn,Mn,Fe)Mn_3O_7.3H_2O$]. The last four are commonly found in the laterite profile. There have been some conflicting interpretations regarding the genesis of these minerals. Ostwald (1988) indicated that they were formed by sedimentary and diagenetic processes whereas Dammer *et al* (1996) believed that the present mineralogy was produced by replacement processes associated with intense chemical weathering during the Tertiary.

Gangue minerals comprise iron oxides, clays and quartz grains. Goethite is the most common iron oxide in ferruginous ores and forms lateritic coatings on Mn-ore pebbles, cobbles and pisoliths. Hematite is also present in ferruginous ores. Kaolinite is the dominant clay mineral in the ore horizon, and minor smectite and illite are present in the surrounding host rocks. Detrital quartz is common, particularly in the lower parts of the ore horizon. It forms sand-sized nuclei in mangan pisolite ore and framework grains (50-500 µm in size) in siliceous manganite ore. Minor amounts of pyrite, glauconite and calcite are present in sandy claystone below the ore horizon.

Reports on the major, minor and trace element geochemistry, and on the rare earth element distribution of the Mn ore and associated rocks are in Pracejus and Bolton (1992) and Pracejus *et al* (1990), respectively. These studies were largely based on unpublished work by Pracejus (1989). A stratigraphic control on the abundance of some minerals is evident in the trace elements. Cryptomelane, todorokite, romanechite and gibbsite usually concentrate in the upper parts of the profile whereas pyrolusite and quartz increase down section (Pracejus and Bolton 1992).

Rosie Creek South

Rosie Creek South is located about 75 km to the northwest of Borroloola in the vicinity of Rosie Creek (on Tawallah Range) and is within the Lorella pastoral lease. BHP Ltd discovered this subsurface deposit by RC drilling Cretaceous sediments adjacent to a prominent upstanding Palaeoproterozoic quartz arenite (Yiyintyi Sandstone) sequence. The locality was targeted using a Groote Eylandt-style Mn exploration model. In 1994, BHP Ltd completed one diamond drillhole totalling 15.3 m and 29 RC drillholes totalling 859 m (Berents 1994).

Manganese mineralisation is hosted in claystone and minor conglomerate at the base of the Cretaceous Walker River Formation, at the unconformity with the underlying

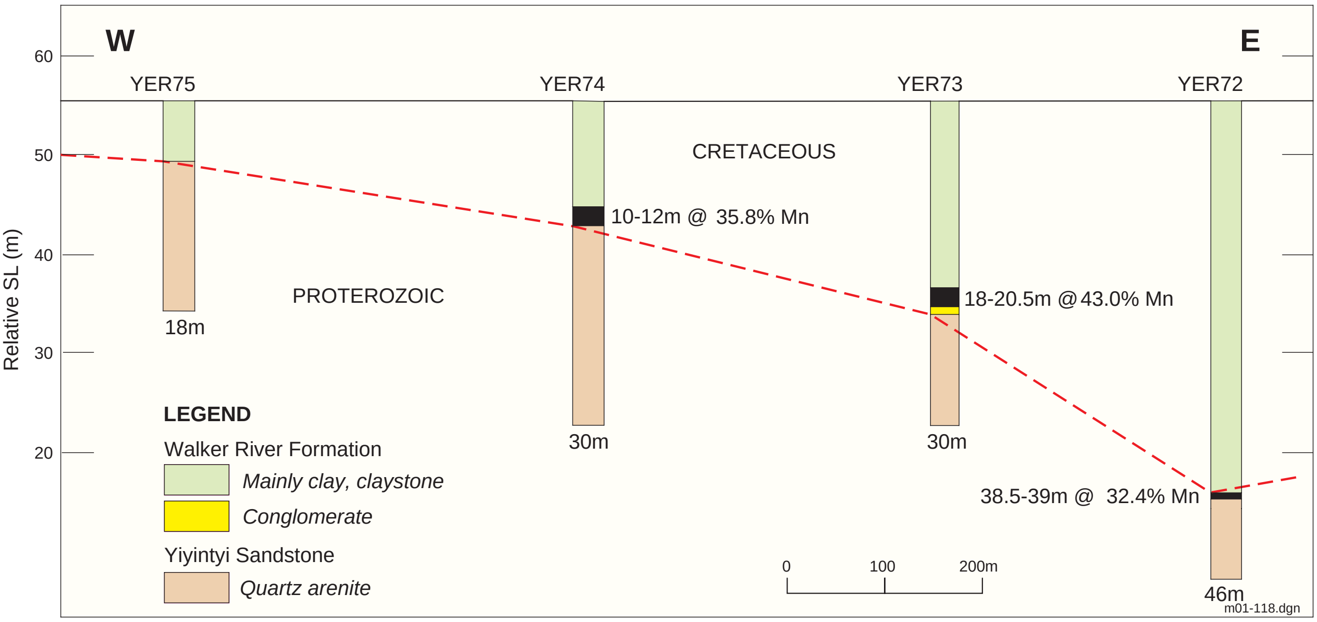

Figure 47. Geological cross section of Rosie Creek South Mn prospect (modified from Berents 1994)

Yiyintyi Sandstone (**Figure 47**). Nine RC holes (**Table 13**) intersected Mn mineralisation, YER73 had the most significant result of 2.5 m @ 43.0% Mn, 14.0% SiO_2, 0.14% P and 3.4% Al_2O_3 from 18 m depth. The tonnages given in **Table 13** were estimated by Berents (1994), who also stated that the deposit may contain 4.5-5.5 Mt at 25% Mn. Details on the methodology for this estimate are unknown. Moderate to high levels of phosphorus (0.08-0.14%) and silica (14.0-31.4%) are present in intercepts containing >30% Mn.

East Arnhem Land

Regional exploration by BHP Ltd between 1964 and 1967 in the *East Arnhem Land* region led to the discovery of the Caledon 1 prospect, which is located in the Caledon Bay area, about 70 km to the southwest of Nhulunbuy. Four prospecting pits were sunk adjacent to a creek that contained exposures of Cretaceous manganiferous sandstone (BHP 1964a). These pits indicated the existence of at least two sandy Mn lenses within a 2 m thick horizon.

The Mn horizon was also identified between the Peter John River and Caledon Bay (BHP 1964a), where it is associated with an interval of mainly argillaceous sediments within a fluvial to shallow marine succession mapped as Yirrkala Formation (Pietsch *et al* 1997). Channel sampling at Pits 1, 4 and 5 indicated that the Mn horizon averages 18% Mn in the Caledon Bay area.

Sandy Mn lenses at *Caledon 1* are thin (0.2-0.4 m) and in places, are overlain by a very thin (5 cm), massive, laminated manganese layer. A channel sample from 3.0-3.5 m depth in Pit 5 assayed 33.1% Mn (BHP 1964a). Mineralisation is in the form of manganese oxides as impregnations and cement in quartz sandstone. Follow-up RC drilling indicated that the mineralisation has no significant vertical or lateral extent (Chesnut *et al* 1967). Surficial enrichment processes have played a major role in this low-grade occurrence.

A similar style of mineralisation was discovered at the *Peter John* prospect, which is located 31 km to the west-southwest of Nhulunbuy (BHP 1964a, b, Chesnut *et al* 1967). A sample from a 0.45 m thick sandy Mn lens assayed 31.7% Mn, 21.4% SiO_2 and 10.3% Fe (BHP 1964a). Follow-up pit sinking and RC drilling indicated that the mineralisation was largely surficial.

Two Mn horizons are located at the northern end of Probable Island (*Probable Island* prospect). A 30 m interval of siltstone and sandstone (Walker River Formation?) separates the two horizons, which are 1.5 m and 2.1 m thick (BHP 1964a, b). A chip sample from the thinner lens assayed 41% Mn, 12.5% SiO_2 and 7.5% Fe.

More recent significant discoveries in the Gulf region include Yiyintyi, Batten Creek and Caledon 2. At *Yiyintyi*,

Hole	Depth (m)	Intercept (m)	Mn %	SiO_2 %	P %	Al_2O_3 %	Tonnage (SG 2.8)
YER52	23.5	0.5	13.6	67.9	0.11	7.3	0.31 Mt
YER53	11.0	0.5	24.0	34.6	0.17	4.6	0.25 Mt
YER65	20.0	2.0	26.4	26.6	0.25	4.3	0.59 Mt
YER66	20.0	2.0	27.8	30.3	0.09	4.6	1.55 Mt
YER67	4.5	0.5	11.7	18.4	0.05	3.1	0.26 Mt
YER71	14.0	1.0	14.4	58.6	0.58	2.6	0.47 Mt
YER73	18.0	2.5	43.0	14.0	0.14	3.4	0.87 Mt
YER74	10.0	2.0	35.8	15.9	0.12	3.1	1.15 Mt
YER78	38.5	0.5	32.4	31.4	0.08	4.0	0.14 Mt

Table 13. South Rosie Creek drilling results (modified from Berents 1994)

initial RC drilling by BHP Ltd intersected 2 m @ 39.2% Mn and 9.2% Fe (YER06) from 20 m depth (Berents *et al* 1994). Follow-up RC drillholes and a diamond drillhole (YED03) indicated that the Mn mineralisation has limited lateral continuity (Rennison *et al* 1995). At the *Batten Creek* prospect, patchy Mn mineralisation was intersected in RC drillhole BC010 (6 m @ 15.1% Mn, unwashed) beneath a TEM anomaly (Paterson 1996). There is very little information on *Caledon 2* other than a reference to outcropping pisolitic manganese material in excess of 2 m in thickness within Cretaceous sediments (Frakes 1990).

Ore genesis

Pracejus *et al* (1988) and Dammer *et al* (1996) have presented reviews of previous models on the genesis of manganese mineralisation at the Groote Eylandt deposit. Most workers considered that manganese oxides were originally precipitated as pisoliths and ooliths in a shallow marine nearshore environment. This interpretation is supported by the occurrences of well documented sedimentary structures, accretionary pisoliths/ooliths and foraminifers at levels below, above and in the ore horizon. Varentsov (1982) suggested that "primary pisolitic ores" resulted from reworking of a pre-existing weathered crust that developed on the underlying manganiferous marl unit. However, this model would infer that the pisoliths were concretionary in origin, and this is inconsistent with interpretations from pisolith studies (Ostwald 1988, 1990, Bolton *et al* 1988).

There has been some debate on the process of Mn-bearing pisolith formation. Bolton *et al* (1988) proposed an inorganic catalytic oxidation process for Mn oxide pisolith formation in an oxidised, agitated, shoaling nearshore marine environment. Ostwald (1990) proposed a biogenic origin for the pisoliths based on the identification of microscopic algal structures and suggested that pyrolusite, which forms the "primary pisoliths", may not represent the original mineralogy. This suggestion was taken a step further by Dammer *et al* (1996) following K-Ar dating of romanechite from the lower parts of quarry G-south. Results indicated a minimum age of 43.7 ± 1.2 Ma, which is about 50 Ma younger than the host sequence. Dates obtained from cryptomelane and Ba todorokite samples indicated precipitation ages of between 6 Ma and 18 Ma. Dammer *et al* (1996) believed that the present mineralogy of the Groote Eylandt ore is entirely the product of intense chemical weathering cycles from the Early Tertiary to the present. If the primary mineralogy has not been preserved, genetic models for this deposit would need to rely on "less altered" comparative deposits (eg Oligocene Chiatura deposit in Russia) or present day analogues.

Slee (1980) suggested that the primary Mn ore was derived from subaerial weathering and erosion of the underlying marl unit. Manganese carbonate in the marl was leached and the Mn transported as a bicarbonate complex in west-flowing streams into oxidising, nearshore marine environments where it precipitated to form Mn oxide pisoliths. Frakes and Bolton (1984) suggested that manganese concentration occurred during an Albian marine transgression in anoxic, organic-rich basin waters. They suggested that manganese oxides were later precipitated during an early Cenomanian marine regression on coastal terraces (**Figure 43**). Precipitation of Mn oxide is thought to occur, initially, via catalytic oxidation onto mainly organic particles and membranes, and then via autocatalytic processes (Bolton *et al* 1988).

Hydrothermal deposits

There are 14 hydrothermal manganese occurrences identified in the Northern Territory, most of which are within the Ashburton province of the Tennant Inlier in HELEN SPRINGS. Six are clustered around the Bootu Syncline (*Bootu Creek* area) and five are in the vicinity of *Renner Springs*. Information on the former area is largely based on recent exploration work (1995-97). Significantly less information is available on the Renner Springs occurrences. The *Wangatinya* prospect, in the western Amadeus Basin is possibly a Cambrian example of this type of mineralisation.

Tennant Inlier

Bootu Creek

The Bootu Creek area (**Figure 7**) is situated within the Banka Banka pastoral lease, which is about 110 km north of Tennant Creek and 10 km east of the Stuart Highway. It contains numerous manganese occurrences including the abandoned Mucketty mine. This area was first pegged in 1954 and small-scale mining from five shallow open cuts commenced in 1955 to supply manganese oxide for the Rum Jungle uranium treatment plant (Jones 1955).

Between 1955 and 1969, about 13 280 t of ore grading about 66% MnO_2 (42% Mn) was mined (**Figure 48**) from the Mucketty deposit (Gamble 1962, Balfour 1989). Encouraging results were obtained from geological mapping and sampling of the deposit by Jones (1955) and the BMR subsequently drilled five shallow diamond drillholes adjacent to the two northern open cuts (MacKay 1956). Post-mining exploration included two percussion holes (MP-1 and MP-2) that were drilled by Esso Australia Ltd (Ward 1983), rock chip sampling by Eupene Exploration (Hickey 1990), and airborne GEOTEM, ground TEM, rock chip sampling and drilling by BHP Ltd in 1995-96 (Nunn 1996, 1997).

The Bootu Creek manganese occurrences lie within the lower Bootu Formation (Hussey *et al* 2001). This unit is folded around the Bootu Syncline, which plunges gently to the north-northwest. Bedding dips at low to moderate angles (10-45º) and averages about 30º. Several north-trending faults

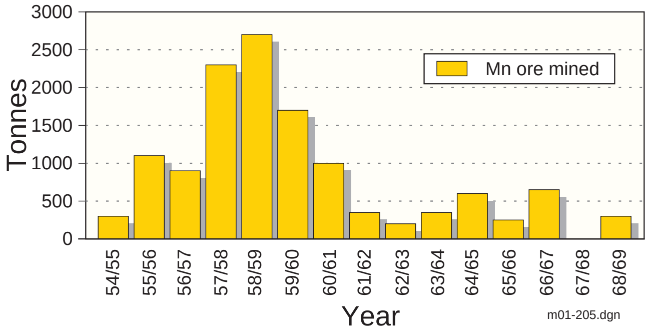

Figure 48. Mucketty manganese mine production

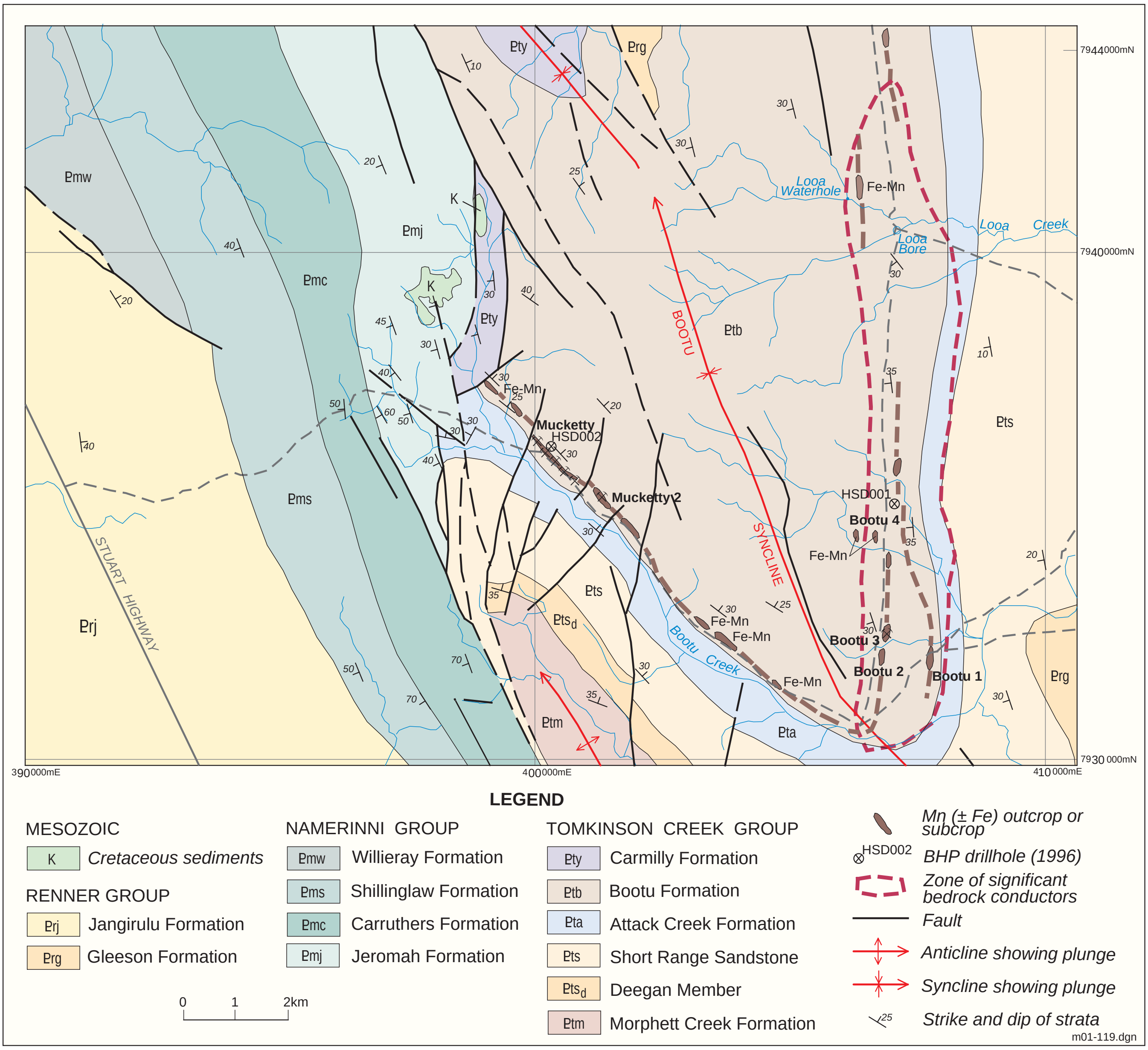

Figure 49. Interpreted geology of Bootu Creek manganese deposits (modified from Hussey *et al* 2001)

have been mapped along the western limb of the Bootu Syncline and these have lateral displacements of up to 300 m.

The manganiferous horizon can be discontinuously traced for 24 km around the syncline as a series of black ridges and knolls (**Figure 49**). Diamond drillhole logs show that there is good lithological correlation from one limb of the Bootu Syncline to the other (Nunn 1997). Manganese oxides, predominantly as amorphous and massive cryptomelane, occur as epigenetic lens and vein replacements in a dolomitic siltstone bed. An overlying scarp-forming sandstone bed is also mineralised, as is a stromatolitic dololutite bed above the hangingwall sandstone, which has been pervasively replaced by manganese oxide. Iron oxide-rich lenses (up to 50% Fe) are also present in the Mn horizon and at slightly higher levels in the stratigraphy (**Figure 49**). Carbonaceous siltstone and dolomite have been intersected below the Mn horizon (Nunn 1997).

At *Mucketty* (also known as Rossi prospect), the manganese ore horizon is up to 8.6 m in thickness and averages 6 m (Crohn 1960). Mining has taken place via shallow open cuts, which are up to 8 m in depth, and which extend over a 760 m strike length. Metallurgical-grade manganese ore (>38% Mn) is up to 2.7 m thick and averages about 1.2 m (Jones 1955). This material is grey to black, massive or reniform in texture and is found toward the base of the ore zone, where the Mn completely replaces siltstone. Pyrolusite is present as veinlets in the massive psilomelane ore (**Figure 50**). Medium-grade ore (22-38% Mn) is grey to black and contains numerous medium to fine quartz grains (Jones 1955). It occurs above the metallurgical-grade ore. The Mn replaces quartz sandstone or partially replaces siltstone and bedding is often preserved. Gangue minerals include quartz, barite, chalcedony, calcite and gypsum. Jones (1955) also described a low-grade ore (6-22% Mn), above the medium-grade ore. This consists of manganiferous sandstone capping a quartz sandstone.

Five shallow diamond drillholes by the BMR (MacKay 1956) and two percussion holes by Esso Australia Ltd (Ward 1983) all failed to intersect metallurgical- or medium-grade manganese ore. A deeper (225 m depth) percussion/diamond

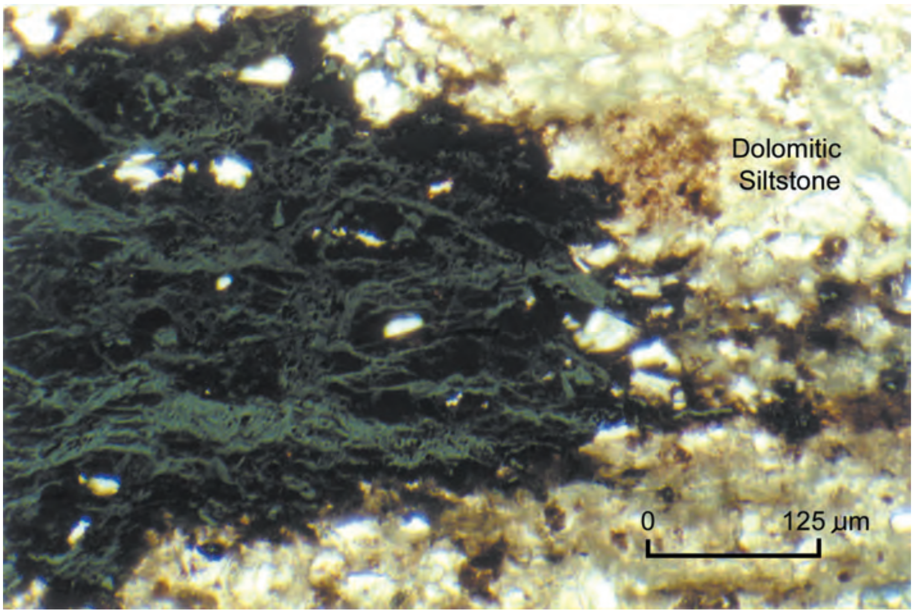

Figure 50. Polished thin section showing pyrolusite veinlets in massive psilomelane ore that is replacing dolomitic siltstone, Mucketty mine from DDH HSD002 at 63.2 m depth (NTGS M01, partly reflected and transmitted light)

drillhole (HSD002) by BHP Ltd intersected 15 m grading 14.75% Mn from 54 m (Nunn 1997). A bedding plane shear appears to have removed most of the favourable siltstone bed and juxtaposed a black pyritic shale against the Mn horizon.

One and a half kilometres to the southeast, at *Mucketty 2* (also known as Deposit C), mining has excavated a 70 m long open cut on a 3-4 m thick manganese horizon that can be traced for 200 m along strike. Jones (1955) described outcrops of medium- and low-grade ore, but chip sampling by Hickey (1990) indicated the presence of higher grade material, which contains up to 55.3% MnO, 5.05% SiO_2 and 0.20% P_2O_5. This manganese horizon dips at 25º to the northeast.

Along the eastern limb of the Bootu Syncline, there are four documented Mn occurrences (*Bootu 1*, *2*, *3* and *4*) that contain metallurgical-grade material (>36% Mn). Outcrop in this area is poor relative to the western limb. Bedding consistently dips at 30-35º to the west. Various companies have conducted rock chip sampling in this vicinity and drilling at Bootu 4 was undertaken by BHP Ltd (Nunn 1997). There are at least two manganese horizons present in a conductive zone (**Figure 49**) that has been outlined by an airborne GEOTEM survey (Nunn 1997).

At *Bootu 1*, a series of costeans have been excavated on a low outcropping ridge that was estimated by Jones (1955) to contain 3000 t of medium-grade ore (22-38% Mn) and less than 50 t of high-grade ore (38-48% Mn). The ore horizon dips moderately to the west at 50º and can be traced for at least 200 m along strike. A rock chip sample by Hickey (1990) assayed 37.3% Mn, 9.12% SiO_2 and 0.07% P, whereas a sample by GEMCO returned 50.6% Mn, 3.6% SiO_2, 4.8% Fe and 0.056% P (D Mallon, GEMCO, pers comm 2000). Ore material consists of porous colloform cryptomelane, and pyrolusite and minor hollandite, which are intergrown with goethite and quartz (AMDEL 2000). Initial shallow drilling in 2001 by Bootu Creek Resources Pty Ltd[3] has outlined an inferred resource of 8.5 mt @ 33% Mn (OM Holdings 2001).

Bootu 2 consists of a 0.6-1.2 m manganese bed, which is exposed over a 120 m strike length (Jones 1955). Samples of three ore types assayed 36.7% Mn, 24.3% SiO_2 for sandy ore, 34.5% Mn, 21.5% SiO_2 for micaceous ore and 50.1% Mn, 2.5% SiO_2 for massive ore (Jones 1955). A chip sample by GEMCO returned 36.0% Mn, 22.0% SiO_2, 1.8% Fe and 0.027% P (D Mallon, GEMCO, pers comm 2000). Mineralogical studies of a bulk sample suggested that massive to weakly developed, colloform-textured cryptomelane is the dominant manganese mineral with minor hollandite (AMDEL 2000). Quartz, goethite and barite are the main gangue minerals.

Bootu 3 consists of a 5-6 m thick manganese bed that has been excavated in the 1950s over a 40 m strike length. A chip sample by Hickey (1990) returned 17.8% Mn, 10.8% SiO_2 and 0.05% P, whereas samples by GEMCO returned up to 49.7% Mn, 1.6% SiO_2, 1.3% Fe and 0.053% P (D Mallon, GEMCO, pers comm 2000). Ore consists of cryptomelane and minor hollandite, which together form aggregates that have a massive to well-developed, banded colloform texture (AMDEL 2000). Only minor amounts of quartz are present in the Mn ore over the strike length.

Bootu 4 (also known as *Deposit E* and *Redwing*) was described by Jones (1955) as a thin band of siltstone partially replaced by manganese and overlain by Mn-stained sandstone. Chip sampling by Hickey (1990) returned up to 39.6% Mn, 1.03% SiO_2 and 0.04% P, and a sample by Nunn (1997) assayed 36.7% Mn. Drilling by BHP Ltd included one percussion/diamond drillhole (HSD001), which reached a depth of 149 m, and four percussion drillholes (HSP003-006). Four of the five drillholes intersected massive manganese mineralisation (**Figure 51**) between 43 m and 75 m below the surface.

Only two drillholes (HSD001 and HSP003) penetrated the entire thickness of the Mn horizon. Results from these indicated the presence of a 9-12 m thick manganese horizon that contains moderate-grade manganese (22.8-36.4% Mn) and low (<0.05%) phosphorous. There are indications of secondary supergene enrichment in HSP003 (2 m @ 47.6% Mn from a vertical depth of 40 m). The two southernmost drillholes intersected the upper section of the same manganese ore lens and these returned similar grades (27.8-36.5% Mn). Drilling has thus identified a manganese horizon at *Bootu 4* that contains moderate-grade Mn over a

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[3] OM Holdings has 60% shareholding in Bootu Creek Resources Pty Ltd.

strike length of 500 m. Geochemical data (**Figure 51**) from three of the percussion holes indicate high levels of silica (33.3-56.5% SiO_2).

A limited surface bulk (10 kg) sampling program by the Northern Territory Department of Mines and Energy to evaluate beneficiation characteristics of the Bootu and Mucketty Mn ores suggested significant variations in ore quality (Smith 2000). Premium-grade Mn ore exists at Bootu 3, siliceous-grade ore (after screening of fines) occurs at Bootu 1 and Mucketty, and unsaleable ore is found at Bootu 2. The lower quality ores at Bootu 2 and Mucketty are not suitable for beneficiation by heavy media separation. Levels of phosphorus (0.01 to 0.04% P) and alumina (1.4 to 5.3% Al_2O_3) in all lump ore fractions are within market specifications, but variable levels of manganese, silica and iron indicate that selective mining and blending of ore would be required.

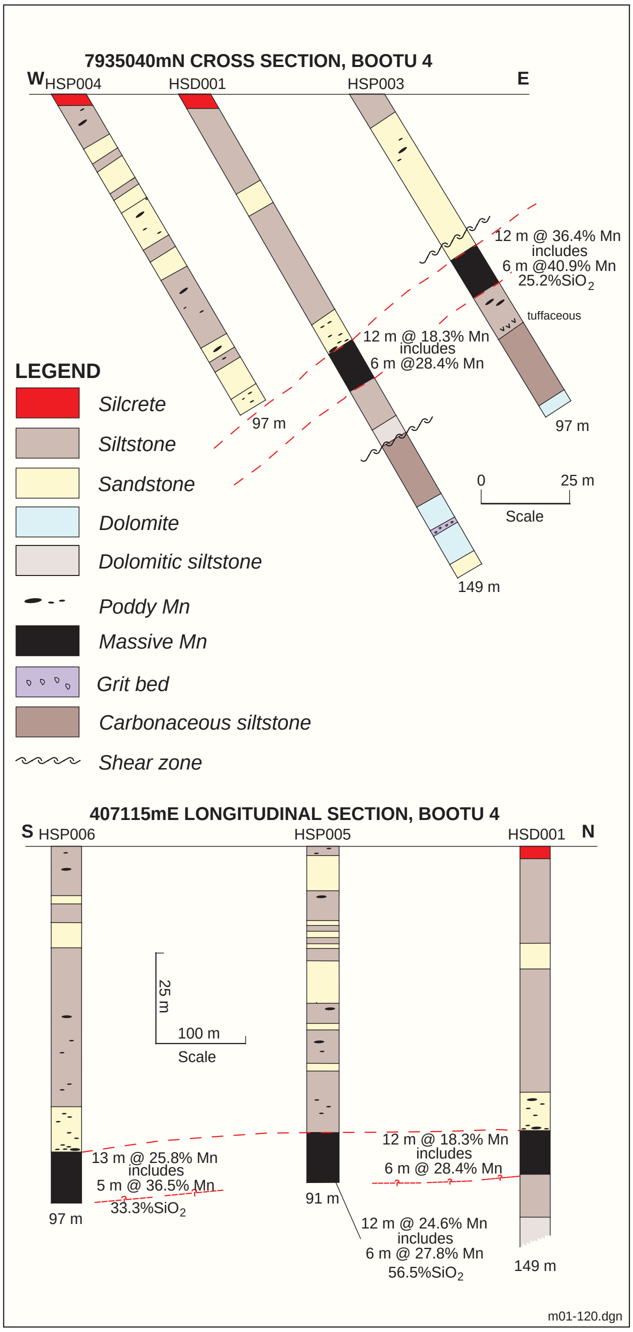

Figure 51. Drillhole intersections of manganese mineralisation at Bootu 4 (modified from Nunn 1997)

Geochemical sampling and drilling results for the eastern Bootu manganese occurrences indicate significant economic potential. The lower 2 m of the ore horizon appears to contain low silica, high-grade manganese. If additional drilling is able to substantiate continuity in ore thickness and grade along the conductive GEOTEM zone, which has a strike length of 13 km, then potential exists for >20 Mt of manganese material to 60 m in depth. Further potential exists for additional or stacked ore lenses (Nunn 1997). The prospective area is situated 110 km north of the Tennant Creek township, 15 km east of the Stuart Highway (sealed road), 50 km east of the pending Alice Springs-Darwin railway and 45 km east of a gas pipeline.

Renner Springs

These prospects are situated about 15 km to the west of Renner Springs Roadhouse (**Figure 7**), within the Renner Springs pastoral lease. The manganese occurrences are so poorly documented that only brief descriptions can be given. The Renner Springs No 1, 2, 3 and 4 occurrences are hosted by sedimentary rocks at the base of the Palaeoproterozoic Shillinglaw Formation. The lower part of this formation consists of interbedded medium to fine sandstone and dololutite (stromatolitic in places), and minor dolomitic mudstone and siltstone (Hussey *et al* 2001).

Some mining from several small pits was carried at *Renner Springs No 1*, from a Mn horizon that can be traced over a strike length of 350 m (Ward 1983). Bedding and the concordant Mn horizon both dip at 20º to the northeast. Jones (1955) described massive manganese ore (44-50% Mn) that contains fragments of unreplaced siltstone. Wygralak (1993) indicated that the manganese mineralisation replaces a brecciated siltstone bed. Prior to any mining, Jones (1955) indicated a resource of 4000 t of ore averaging 31% Mn per vertical foot to a shallow depth of less than 3 m.

A percussion drillhole that was located 12 km to the south-southwest of Renner Springs (*W38RDH*) by Key Resources NL intersected 9 m grading 36.7% Mn, including 3 m @ 42.4% Mn from 63 m depth (Ward 1987). This hole was collared in poorly exposed Cretaceous rocks but appears to have intersected the Mn horizon in brown siltstone near the base for the Shillinglaw Formation. A hypogene mineralisation model is probably applicable to these manganese occurrences.

The only other significant occurrence in this area is at *Renner Springs No 5* (AMG 361830mE 7971470mN), where manganese mineralisation is present in lithologies mapped as Cretaceous (Hussey *et al* 2001). Jones (1955) described the occurrence as essentially containing low-grade ore (<22% Mn) and pockets of medium-grade ore (22-38% Mn). It is characterised by Mn partially replacing siltstone and chert.

Amadeus Basin

Wangatinya prospect is located in a remote area within the Haasts Bluff Aboriginal Land Trust on MOUNT LIEBIG, 280 km to the west of Alice Springs (**Figure 8**). It is hosted in the basal portion of the Late Cambrian Pacoota Sandstone (unit P4 of Gorter 1991). Shallow marine, friable, medium to fine quartz sandstone hosts the mineralisation. Bedding in the area dips steeply at 60-65° to the north. The friable nature of outcrops is probably due to weathering and the dissolution of carbonate cement in the sandstone. The following description is based on Morlock (1972).

Mn-Fe mineralisation occurs as a series of massive, bedding concordant lenses, the largest being 53 m in length and 7.6 m in thickness. These lenses and pods are confined to two beds that total about 30 m in thickness and can be traced for 260 m along strike. A network of Mn veinlets envelops the lenses and infills fractures and joints in between. Mineralisation is in the form of pyrolusite, psilomelane and iron oxides (mainly goethite and limonite). Nine random grab samples from the lenses averaged 44.3% Mn and ranged between 13.6-55.0%. Seven of the nine samples contained >40% Mn. Silica, phosphorus, iron and alumina contents were not analysed.

There are insufficient data to confidently determine the genesis of the mineralisation, but the close association with iron oxides, discontinuous (poddy) nature of the occurrences and epigenetic textures suggest a hydrothermal origin. Secondary supergene processes have played a significant role in upgrading the mineralisation. Further untested potential exists along strike in both directions under alluvial cover. However, given the remote location and current small tonnage amenable to open cut mining, economic development of this deposit is unlikely.

Ore genesis

At a regional scale, a clear stratigraphic control is evident over the manganese deposits in the Bootu Creek and Renner Springs areas. A manganese horizon at the base of the Bootu Formation is known from near Attack Creek on FLYNN (Ferenczi 1997b) and this indicates a regional distribution of the mineralising event. The basal sections of the host units (Bootu and Shillinglaw Formations) both contain interbedded sandstone, dololutite and dolomitic siltstone. Both host units overlie dominantly carbonate-mudstone sequences (Attack Creek and Carruthers Formations, respectively). Major faults are also present in the vicinity of the manganese occurrences.

Surface and subsurface (meso- and microscopic) observations indicate that the manganese is epigenetic. Siltstone and sandstone are both mineralised; pervasive replacement of the former is common and leads to the formation of massive manganese ore lenses. Massive manganese oxide replacement of a stromatolitic dololutite bed at the Mucketty mine suggests that Mn mineralisation is not syn-sedimentary.

Trace element concentrations of cobalt, copper and lead are relatively high in Bootu Creek manganese ore relative to Groote Eylandt oolitic and pisolitic ore (**Table 14**). However, nickel and vanadium levels in Groote Eylandt ore are higher than those of Bootu ore. Nicholson (1992) has used mineralogical and geochemical enrichments to distinguish between different genetic types of Mn deposits. However, this technique does not differentiate sedimentary brine-derived Mn from the others.

Epigenetic manganese occurrences in southern Israel (Ilani *et al* 1990) contain elevated copper (up to 330 ppm), cobalt (1800 ppm), nickel (1100 ppm), lead (600 ppm) and zinc (5000 ppm) values that are comparable to those of typical Bootu material. These Israeli manganese- and iron oxide-bearing veins and lenses are closely associated with fault zones that crosscut Cretaceous marine carbonates. Ilani *et al* proposed a genetic model that involves the leaching of Mn, Fe and trace metals from basic igneous rocks via the circulation of deep-seated brines. The metal-rich brines ascended along major fault zones and precipitated the metals when carbonates were encountered.

A similar mechanism may account for the mineralisation at Bootu Creek and Renner Springs, whereby metals might have been leached from sediments and basic volcanics within the Hayward Creek Formation and then transported as metal-rich brines under reducing and slightly acid conditions within marine sandstone aquifers (eg upper sections of Bootu and Shillinglaw Formations). The generation of low temperature (60-100ºC) Mn and trace metal fluids may have been related to basin dewatering or minor hydrothermal activity associated with distal magmatic or tectonic events. Manganese oxides, iron oxides and trace metals would have been precipitated when the brine encountered a redox barrier (alkaline and oxidising conditions). Dolomitic siltstones in basal sections of the host formations may have provided the appropriate chemical environment for this to occur.

Alternatively, the Mn horizons may have had a sedimentary origin. The initial Mn deposits may then have been modified by brine activity so as to generate epigenetic textures and an elevated base metal geochemistry.

Surficial Deposits

Some 98 surficial Mn occurrences have been recorded in the Northern Territory. These occurrences are present in the McArthur (86), Amadeus (2), Eromanga (1) and Victoria-Birrindudu Basins (2), the Pine Creek Orogen (3), the Tennant Inlier (2) and the Arunta province (2). Many more are recorded in company reports but have not been entered into the NTGS MODAT database, as they are geologically insignificant and have little or no economic potential.

McArthur Basin

A number of small manganese occurrences are located in the Calvert River-Robinson River area of the southern McArthur Basin (**Figure 9**). These occurrences include Masterton No2, Robinson River No1 and No2, Camp No1, Manganese 1, Manganese 2 and Photo and are hosted in chert and dolomite assigned to the Karns Dolomite. The Masterton No2 prospect is the largest, and has attracted some interest from small exploration companies and prospectors.

Masterton No2 (also known as Calvert Hills Mn prospect No1) is located within the Calvert Hills pastoral lease, about 14 km to the northeast of Calvert Hills homestead. This prospect was first mapped and sampled by Enterprise Exploration Ltd (Murray 1953); a sample from one of the outcrops assayed 63.32% Mn, 7.37% SiO_2, 1.57% Fe, 0.43% P and 0.51% Al_2O_3. Shannon (1971) produced a more detailed geological map and carried out additional sampling.

Table 14. Trace element geochemistry of selected Mn ores (in ppm) from Bootu, Renner Springs and Groote Eylandt. Source: Nunn (1996, 1997), Ward (1983, 1987) and Pracejus (1989)

	Co	Cu	Ni	V	Pb	Zn
BOOTU						
Surface						
average	1554	5405	24	142	5581	193
maximum	3256	32 500	52	739	22 000	593
minimum	200	300	<2	14	40	24
n	17	17	13	13	17	17
Subsurface						
average	530	975	34	43	886	108
maximum	856	1637	74	69	5205	200
minimum	211	245	22	28	111	51
n	13	13	6	6	13	13
RENNER SPRINGS						
Subsurface						
average	420	66	71	-	-	519
maximum	575	80	80	-	-	645
minimum	185	35	55	-	-	260
n	4	4	4	-	-	4
GROOTE EYLANDT						
Cemented oolites						
average	77	139	342	331	57	115
maximum	134	185	427	493	58	162
minimum	36	99	258	257	56	99
n	8	8	8	8	2	8
Cemented pisolites						
average	95	90	132	201	41	98
maximum	172	191	344	516	72	186
minimum	36	43	28	37	23	65
n	31	31	31	31	14	31

Assay results indicated the existence of material containing 41-51% Mn. Prospectors Niddrie and Erickson inspected and pegged the occurrence with the expectation of proving a 500 000 t manganese resource (Shields 1983, Erickson 1983). Five RC holes totalling 160 m were subsequently drilled into three of the largest exposures (**Figure 52**). This drilling indicated that the manganese mineralisation is surficial and is limited to 2-4 m in thickness on average (Goulevitch 1990).

The Karns Dolomite comprises gently dipping laminated and stromatolitic chert and dololutite, which was deposited in a shallow marine environment. Manganese, mainly in the form of psilomelane, outcrops as discontinuous irregular lenses over an aggregate strike length of 1370 m (Shannon 1971).

The largest lens is 160 m in length and averages 10 m in thickness (up to 25 m at the southern end). Most lenses contain 10-40% chert bands and fragments and are orientated along two directions: 070° and 100° (**Figure 52**). These orientations are most probably joint controlled, as suggested by Shannon (1971) and Shields (1983). Subvertical to moderately dipping joints are common in the manganese lenses (**Figure 52**) and the 070° and 100° orientations are identical to those in another nearby Mn prospect (*Manganese No3*) and to joint patterns in Karns Dolomite in the area (Ahmad and Wygralak 1989).

Regional geochemical sampling by Campe and Gausden (1970) indicated that dololutite within the Karns Dolomite is relatively Mn-rich and averaged 2000 ppm Mn. This suggests that surficial enrichment along joints in Mn-rich dololutite may have produced the thin manganese lenses. Goulevitch (1990) estimated a recoverable resource of 40-50 000 t grading 50% MnO_2.

Regional exploration by BHP between 1964 and 1967 in East Arnhem Land (Chesnut *et al* 1967) identified about 70 manganese occurrences (**Figure 9**), but few details on these are available. Only two of the occurrences (*Caledon 1* and *Peter John*) could be regarded as being possibly sedimentary in origin and the remainder are essentially surficial or secondary. Surficial manganese in the Arnhem Land region occurs either as fragments or pisoliths in laterite or as staining on bedrock. The main mineral forming manganese fragments is cryptomelane (Frakes 1990). Pisoliths tend to be ferro-manganese in composition. Manganiferous laterites are found between Lake Evella and Gove and on Round Hill Island (Frakes 1990, Krassay 1994b). At the *Round Hill Island* prospect, laterites contain loose blocks of pisolitic manganese that may represent primary ore material (Frakes 1990). Chesnut *et al* (1967) reported manganese staining and irregular veinlets in lateritic material in the East Arnhem Land area.

Manganese staining is widespread and is present in Cretaceous sediment and all types of bedrock across East Arnhem Land. The manganese typically forms a crust, about a millimetre thick on rock joint faces and bedding planes, and has precipitated from percolating surface and ground waters. The source of the Mn might be Proterozoic carbonates or basic volcanics, or manganiferous Cretaceous sediments. Proterozoic carbonate and basic volcanic rocks are common throughout the McArthur Basin and mineral occurrences defined by the presence

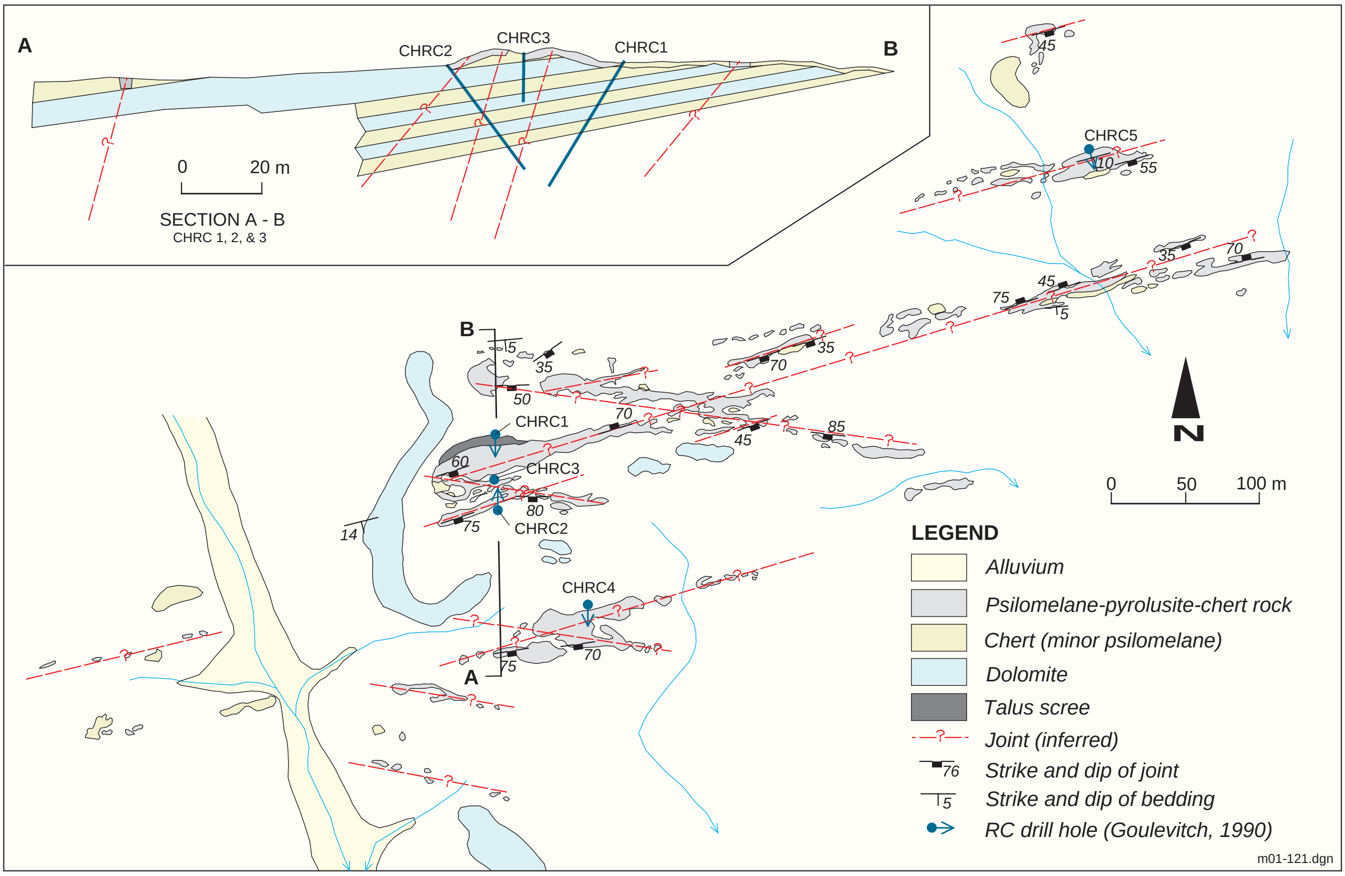

Figure 52. Geological map and cross section of Masterton No 2 prospect (modified from Murray 1953, Shannon 1971, Goulevitch 1990)

of Mn staining in this region can therefore be considered to be largely insignificant.

Dunmarra Basin

McLean's prospect is situated on the western side of a north-trending mesa, about 22 km to the west-northwest of Hayes Creek Inn, within the Douglas pastoral lease. Small-scale mining of the deposit commenced soon after its discovery in 1954, in order to supply the Rum Jungle uranium treatment plant (Dunn 1955). Ore was obtained by breaking and hand picking boulders of massive pyrolusite-bearing siltstone breccia from a talus deposit around the mesa. Total recorded production was 540 t of ore grading 60% MnO_2 (McLeod 1965). The mesa consists of gently dipping Cretaceous siltstone and ferruginous sandstone, referred to the Petrel Formation, which unconformably overlies steeply dipping metagreywacke and slate of the Burrell Creek Formation. Manganiferous boulders were derived from a siliceous siltstone bed that has undergone partial to pervasive pyrolusite replacement at the base of the Petrel Formation. The same style of Mn mineralisation is present at the *Green Ant Creek* manganese deposit, about 4.5 km to the west-northwest, where the Petrel Formation overlies the Cambrian Tindall Limestone (Kruse *et al* 1990). The adjacent *Mount Shoobridge* prospect contains iron ore with minor manganese mineralisation at the base of the Petrel Formation (Perrino 1967).

Other occurrences

Fenn Gap Mn prospect is located in the MacDonnell Ranges, about 25 km to the southwest of Alice Springs, and is in dolostone assigned to the Loves Creek Member of the Bitter Springs Formation (*Amadeus Basin*). Seven chip samples by the NTGS (1970) averaged 39.0% Mn (maximum 50.9% Mn). The prospect is in a west-trending, sub-vertical, pyrolusite-stained brecciated dolostone, which has a strike length of at least four kilometres. The fault-controlled manganiferous horizon is gossanous in places, but manganese mineralisation is limited to surface staining and the infilling of joints and bedding planes.

Two manganese occurrences (*Battle Creek 1* and *Battle Creek 2*) are hosted in the Mesoproterozoic Battle Creek Formation (Victoria-Birrindudu Basin), in VICTORIA RIVER DOWNS (Collins 1970). Battle Creek 1 contains crystalline pyrolusite that infills joints and fractures in dolomite (Sweet 1973). Battle Creek 2 contains manganese as nodules and coatings in a purple calcareous siltstone (Sampey 1969). Regional sampling of the host formation indicates that it is a manganiferous, shallow marine, carbonate sequence (Sweet 1973). Both occurrences are located very close to an unconformity between the Battle Creek Formation and Cambrian continental flood basalt (Antrim Plateau Volcanics).

Black manganiferous laterite pods have developed in places over the Algamba Dolomite Member (Arunta province) in the Reynolds Range area (Stewart *et al* 1980).

A chip sample from the laterite at AMG 266230mE 7541760mN assayed 58% Mn, 1200 ppm Pb, 1100 ppm Zn and 730 ppm Cu (Stewart *et al* 1980). These laterite pods are too small to be of significant economic interest.

MANGANESE PROSPECTIVITY

Significant potential exists for the discovery and development of sizeable manganese deposits in the Northern Territory. Basins that host sedimentary Mn mineralisation have particularly high prospectivity (**Figure 53**). Economic deposits might occur within shallow marine Cretaceous sediments in the Carpentaria Basin, Palaeoproterozoic sediments in the Renner Springs district and Late Cambrian sediments to the west of Alice Springs.

The western and southern margins of the Carpentaria Basin remain highly prospective for Groote Eylandt-style mineralisation. Areas of shallow marine sediments within the Late Albian shoreline (**Figure 53**) have particularly high potential. Follow-up sampling is required in places where pisolitic manganese mineralisation is exposed at the surface (eg Caledon 2 and Probable Island). GEOTEM airborne EM surveys could be used to cover extensive areas that lack outcrop or with poor access. Some reconnaissance work has been undertaken on sediments of equivalent age in the Money Shoal Basin (Wangarlu Mudstone and Moonkinu Sandstone) and one Mn occurrence has been reported (Hughes 1978).

Extensive stratabound manganese mineralisation is present in two Palaeoproterozoic sedimentary units in the Renner Springs district. The Bootu Creek area contains manganese lenses up to 12 m thick in the lower Bootu Formation that can be discontinuously traced for 24 km around a broad syncline. Geophysical, drilling and assay data suggest that multiple lenses containing 30-50% Mn are present over a 13 km strike length along the eastern limb of the syncline. This may represent a near surface resource (at depths <60 m) in excess of 20 Mt. A shallow drilling program is required to determine the grade, thickness and continuity of the ore-grade material. Untested manganese occurrences in the lower Bootu Formation are present in other areas within the Renner Springs district.

The manganese horizon near the base of the Shillinglaw Formation is exposed at several locations over a 6 km strike length, just to the west of Renner Springs roadhouse. There is very limited information on the grade and thickness of the manganese mineralisation other than a single drillhole intersection of 9 m grading 36.7% Mn (including 3 m @ 42.4% Mn). Geological mapping, geochemical sampling, ground geophysics (gravity or EM) and follow-up drilling are required to determine any resource potential for this Mn horizon.

Manganese mineralisation at Wangatinya, 280 km to the west of Alice Springs, consists of a series of massive, bedding-concordant lenses that average about 44% Mn (based on nine rock chip samples). More geochemical sampling and mapping are required to determine the full potential of this prospect. Follow-up work could also target shallowly dipping Pacoota Sandstone in the surrounding area using GEOTEM airborne EM. A substantial tonnage of high-grade ore would need to be outlined for this deposit to be economically viable, due to the remoteness of the area.

A surficial Mn deposit near Calvert Hills (Masterton No2) contains small tonnages of high-grade (50% Mn) material that may meet the requirements for locally based mining or mineral processing operations.

BAUXITE

Definition and classification

Aluminium (Al) is the most common metallic element in the Earth's crust. It is a tough, lightweight metal (SG 2.7) that is resistant to atmospheric corrosion and a good conductor of electricity. Because of these properties aluminium has become an important metal in a great variety of industries.

When combined with oxygen and hydrogen, aluminium forms bauxite. This is the principal ore-type and main commercial source of aluminium. Bauxite consists of mixtures of aluminium hydroxide minerals and impurities. The three minerals that form bauxite are gibbsite, boehmite and diaspore (**Table 15**).

Deposits composed of gibbsite are classified as trihydrate-type, because this mineral contains three water molecules, whereas deposits dominated by boehmite or diaspore are referred to as monohydrate types. Trihydrate bauxite is cheaper to process than the monohydrate varieties because it is more soluble during the Bayer alumina extraction process. The pure anhydrous oxide of aluminium, alumina (Al_2O_3), contains 52.9% Al.

Bauxite is a member of the laterite group of rocks, and is characterised by a particular enrichment of free aluminium hydroxide minerals (**Figure 54**). Laterites are the products of intense subaerial weathering and leaching. This process produces rocks that have higher Fe and/or Al, and lower Si contents than the parent rocks (Schellmann 1983). Bauxite ore contains sufficiently high levels of Al_2O_3 and low levels of clay, silica and Fe_2O_3 to be economically minable.

Bauxite deposits can be classified into three types, according to Bardossy and Aleva (1990):

- *Lateritic bauxites* are residual deposits derived from underlying aluminosilicate rocks;
- *Tikhivin-type bauxites* are detrital deposits overlying the eroded surface of aluminosilicate rocks; and
- *Karst bauxites* are deposits overlying the more or less karstified surface of carbonate rocks.

This classification is essentially based on mode of formation and occurrence, although there are bauxites that are transitional between the three deposit types. About 88% of global bauxite resources belong to the lateritic bauxite group, 11.5% to the karst bauxites and 0.5% to the Tikhivin-type (Bardossy and Aleva 1990). Hill and Ostojic (1984) subdivided lateritic and karstic bauxites into 10 ore types based on relative proportions of aluminium hydroxide minerals and iron oxides (**Table 16**). This techno-economic classification attempts to assist in the identification of high- and low-quality bauxite deposits, the former being gibbsite-dominated and low in iron oxide. Such characteristics are desirable for both metallurgical and non-metallurgical purposes.

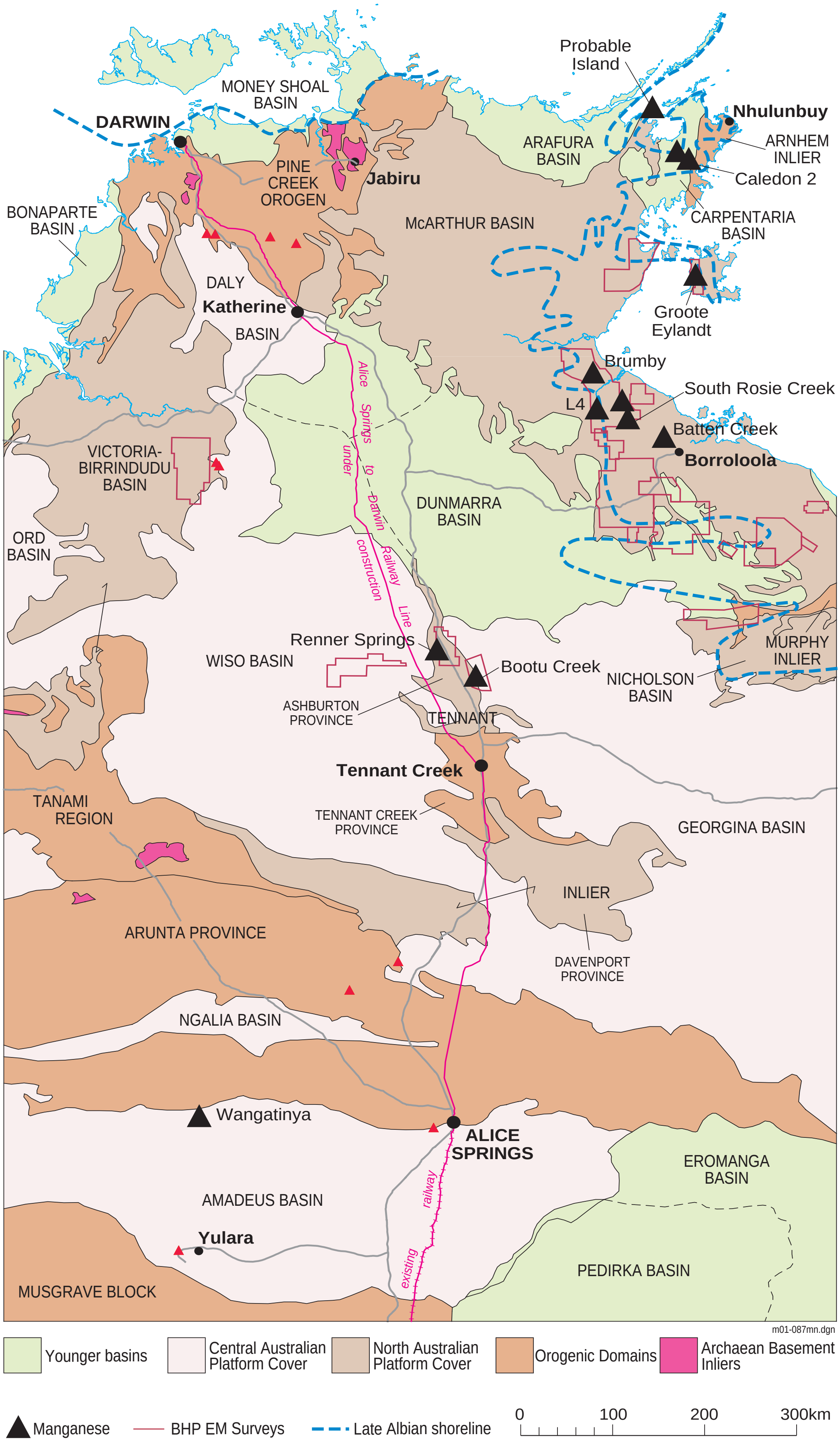

Figure 53. Manganese prospectivity in the Northern Territory

Table 15. Properties of bauxite minerals

Mineral	Chemical composition	Al_2O_3 %	SG	Hardness
Gibbsite	$Al_2O_3.3H_2O$	65.35	2.3-2.4	2.3-3.
Boehmite	$Al_2O_3.H_2O$	84.97	3.01-3.06	4-5
Diaspore	$Al_2O_3.H_2O$	84.98	3.3-3.5	6.5-7

Table 16. Classification of bauxite based on ore character (modified from Hill and Ostojic 1984)

Bauxite type / subtype	Bauxite minerals	Country	Deposit / mine
A. LATERITIC			
(1) Iron Oxide (<10%)			
(a) Guyana	Gibbsite (<3% boehmite)	Brazil	Pocos de Caldas, Trombetas
		Suriname	Moengo, Lelydrop
		Guinea	Sangaredi (lower)
		Guyana	Linden, Ituni, Kwakwani
(b) Weipa	Gibbsite + boehmite (5-20%)	Australia	Weipa
		Guinea	Sangaredi (upper)
		India	Gujarat States
(2) Iron Oxide (>10%)			
(a) Darling Range	Gibbsite (<3% boehmite)	Australia	Gove, Jarrahdale, Del Park, Worsley
		Brazil	Saramenha, Paragominas
		Guinea	Kindia, Dabola
		Indonesia	Bintan Island
		India	Orissa, Belgaum, Andhra Pradesh
(b) Ghana	Gibbsite + boehmite (5-20%)	Australia	Mitchell Plateau
		Ghana	Awaso
		India	Phutkepahar, Madhya Pradesh
B. KARST			
Iron Oxide (>10%)			
(a) Jamaica-1	Gibbsite (<3% boehmite)	Jamaica	Williamsfield, Schwallenburg
		Dominican Republic	Pedernales (LTD)
(b) Jamaica-2	Gibbsite + boehmite (5-20%)	Jamaica	Essex Valley, Mocho, Lydford
		Haiti	Rochelois Plateau
(c) Jamaica-3	Gibbsite + boehmite (5-20%) + Al goethite	Jamaica	Magotty
(d) Mediterranean-1	Gibbsite + boehmite (~50%)	Yugoslavia	Obrovac
(e) Mediterranean-2	Boehmite (>10%) + gibbsite	France	Provnece, Languedoc
		Hungary	Halimba, Padragkut
(f) Mediterranean-3	Diaspore (>10%) and boehmite	Greece	Parnassus
		China	Kwinin

Table 17. Countries with significant bauxite resources and past production (data from Bardossy and Aleva 1990 and USGS)

Country	Bauxite Resource (Mt)	(%)	Historic Production (Mt)	(%)	Production 1999 (Mt)	(%)
Guinea	8600	25.0	381	11.0	15	12.0
Australia	7000	21.0	1115	32.0	46.5	38.0
Brazil	4900	14.5	180	5.1	11.8	10.0
Vietnam	3300	10.0	-		-	
India	2300	7.0	100	2.8	7.0	6.0
Jamaica	2000	6.0	429	12.0	11.6	10.0
Indonesia	1000	3.0	45	1.3	1.0	0.8
Venezuela	350	1.0	36	1.0	4.5	4.0
Cameroon	1000	3.0	-		-	
Suriname	600	2.0	216	6.1	3.7	3.0
USSR (pre-1992) Russia and Kazakhstan	300	1.0	190	5.4	3.5	3.0
China	2000	6.0	85	2.4	8.5	7.0
Guyana	900	3.0	141	4.0	1.8	1.5
Greece	500	1.4	86	2.4	1.9	1.5
Hungary	250	0.7	100	2.8	1.0	0.8

Bauxite deposits are widely distributed throughout the world and occur in a variety of geological, climatic and geomorphic settings. However, they are predominantly found in provinces where aluminous rocks have been subjected to prolonged tropical to subtropical chemical weathering during the Tertiary period. The largest known economic resources occur in Guinea and Australia (Table 17). Global bauxite resources have been estimated by the US Geological Survey at 35 000 Mt (Plunkert 2001). Total bauxite production for 1999 was 123 Mt (Table 17) and Australia was the leading

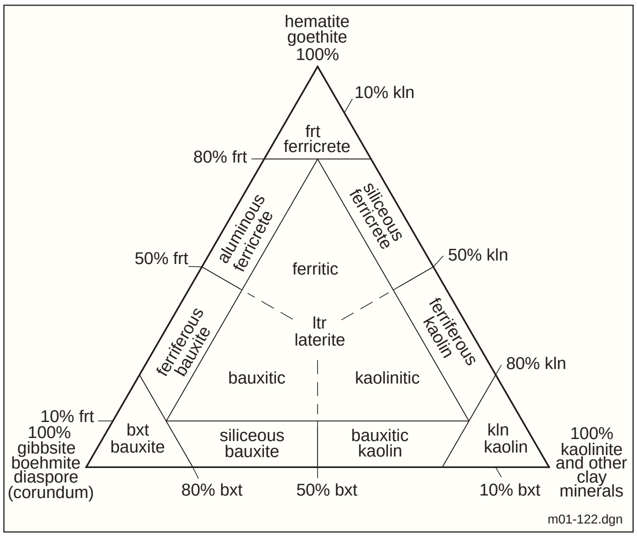

Figure 54. Bauxite rock classification (after Bardossy and Aleva 1990)

producer with an annual output of 46.5 Mt. In Australia, bauxite is mined from large deposits at Weipa (Qld), Nhulunbuy (NT) and the Darling Ranges (WA). Large sub-economic deposits in the Mitchell Plateau and Cape Bougainville regions of northern Western Australia represent a potentially viable future resource.

The following descriptions on the characteristics and genesis of bauxite deposits are focussed on lateritic bauxites as they form the bulk of global, Australian and Northern Territory resources. Refer to Bardossy (1982, 1984) for descriptions of Tikhivin-type and Karst bauxite deposits.

Lateritisation and bauxite formation

Lateritisation is essentially the adjustment of the structure, composition and mineral assemblage of parent rock to the conditions of the Earth's surface under a wet climate. The main agents are physical and chemical weathering processes, the latter being more active than the former in a flat-lying tropical setting.

During lateritic weathering, successive horizons typically develop on parent rock over a period of 10^5-10^7 years. The complete *in situ* profile is composed of up to five horizons (**Figure 55**), some of which can be split into two or more zones:

- *Soil* can be *in situ* or transported. When *in situ*, it is composed of the mechanical and chemical weathering products of the underlying horizon. These are mixed with plant remains and organic matter.
- *Duricrust* constitutes a hard, heterogeneous or homogeneous textured zone dominated by Fe and/or Al hydroxides. In more arid climates, the accumulation of SiO_2 (silcrete) or $CaCO_3$ (calcrete) may occur. The horizon can be subdivided into various zones, based on the predominant composition (eg Al forms bauxite, Fe forms ferricrete) and on textures (eg pisolitic, nodular and tubular). This zone of Fe and Al hydroxide accumulation is commonly referred to as laterite and can be *in situ* or transported and recemented/uncemented.
- The *mottled zone* is essentially a transition zone between the duricrust, where Al and Fe accumulate and the pallid zone, where Fe is leached. Fine kaolinite and quartz grains comprise a soft, light-coloured matrix for brown to red-purple, indurated Fe/Al hydroxide concretions and lenses.
- The *pallid zone* is also known as the clay zone. It consists of fine to very fine, soft, generally massive, light-coloured (whitish) material, which is composed mostly of kaolinite and minor quartz. The presence of this zone is likely to indicate a change in formative conditions, from a low level, high water table environment to a high level, low water table position. This generally follows elevation and incision of the land surface (McFarlane 1983).
- *Saprolite* is *in situ* weathered parent rock. It forms with little volume change, retains traces of parent rock structures and contains corestones in the lower parts. The mottled and pallid zones are often included in descriptions of the saprolite horizon (eg Bardossy and Aleva 1990).
- *Parent rock* is the material, from which the weathering profile is derived. It can be slightly weathered or completely weathered and unrecognisable. In deeply weathered profiles, the first indication of fresh parent rock may be at a depth in excess of 100 m below the surface.

Nahon (1986) has described the stages in which the minerals and fabric of parent rock are broken down and new pedological rock types in the laterite profile are formed (**Figure 55**). Two main geochemical processes are recognised: (1) iron accumulates and replaces quartz and kaolinite via chemical weathering (eg oxidation, dissolution and hydrolysis), so as to form Al-bearing iron hydroxide nodules; and (2) iron is mobile and migrates, allowing kaolinite to be dissolved and removed or reprecipitated as gibbsite. Small-scale migrations and accumulations of iron are continuously repeated and are driven by variations in Eh conditions.

At first, the iron segregations are soft and weakly crystalline, but they develop into hard, crystalline nodules and pisoliths. As the crystalline phase becomes more continuous, pisoliths can coalesce to form a massive ferricrete that may be nodular, tubular or vesicular. Other processes that can lead to ferricrete development include:

- the continuous accumulation of iron within the upper horizon of a descending column of weathered rock, as both ground surface and weathering front are simultaneously lowered (McFarlane 1991); and
- the lateral movement of iron in groundwater into depressions and valley swamps that subsequently become positive relief features by relief inversion (Maignien 1966).

Bauxites are considered to be very mature duricrust, because both iron and silica have been leached from the horizon. Ghosh and McFarlane (1984) have proposed a two-stage model for the development of bauxite profiles. This involves the leaching of silica (Stage 1), followed by the leaching of silica and Fe_2O_3 and the relative accumulation of Al_2O_3 (Stage 2). The ferric ion becomes mobile in hydromorphic

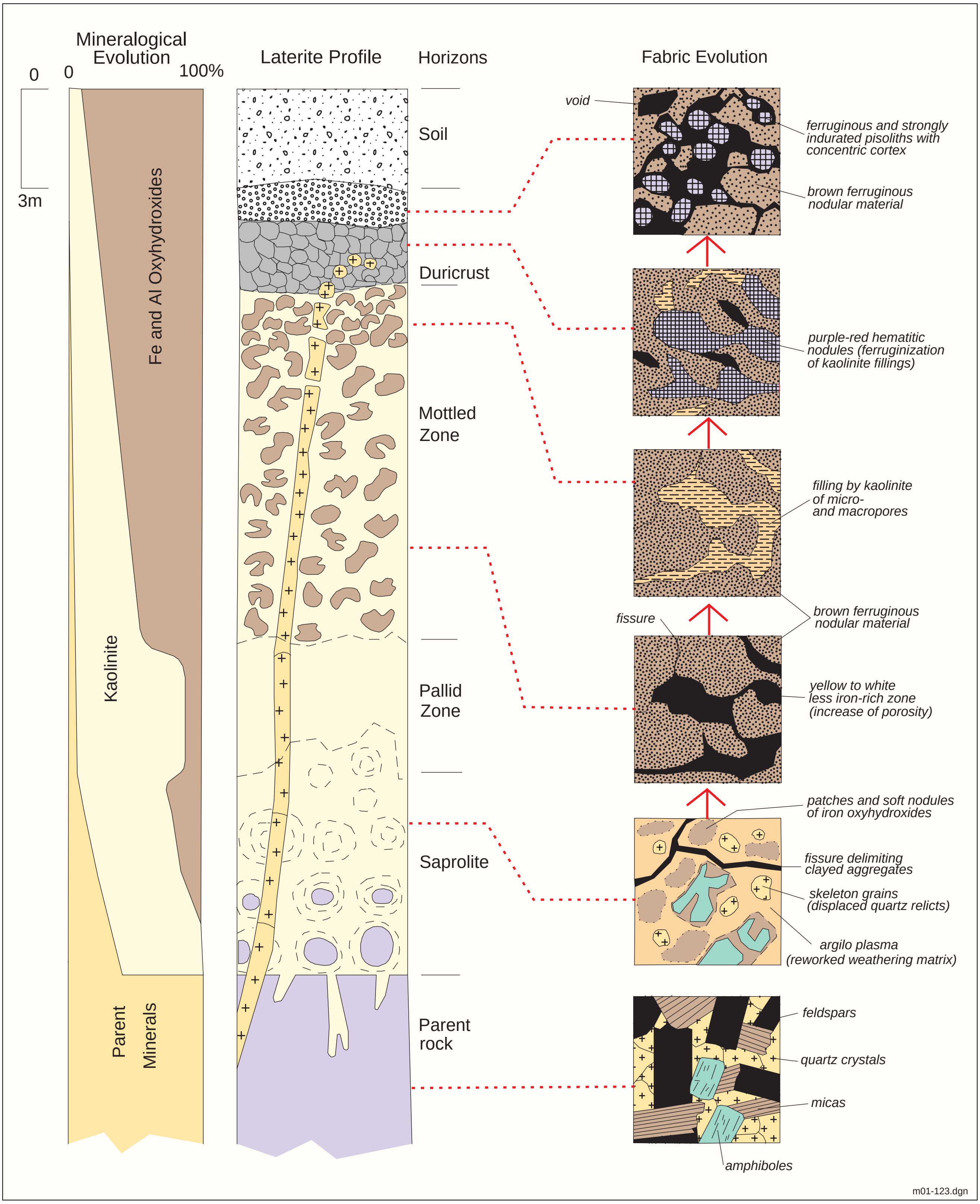

Figure 55. Generalised bauxite profile and evolution (modified from Nahon 1986)

environments, in which the pH is slightly acidic (pH 5 to 6) and Eh is slightly reduced (Norton 1973). Such conditions are present in the upper parts of the duricrust where various biotic processes are active. Iron is leached by humic acids and then removed as organo-metallic complexes (chelation) under low Eh conditions where Al hydroxides remain insoluble.

Bauxite genesis is therefore somewhat restricted to stable tectonic environments that have favourable leaching and drainage conditions. These conditions are enhanced by a tropical monsoonal climate, a permeable aluminous parent rock, high levels of biological (both macro-and micro) activity, which generate a low Eh, and low to intermediate pH groundwater. An incised elevated plateau promotes free

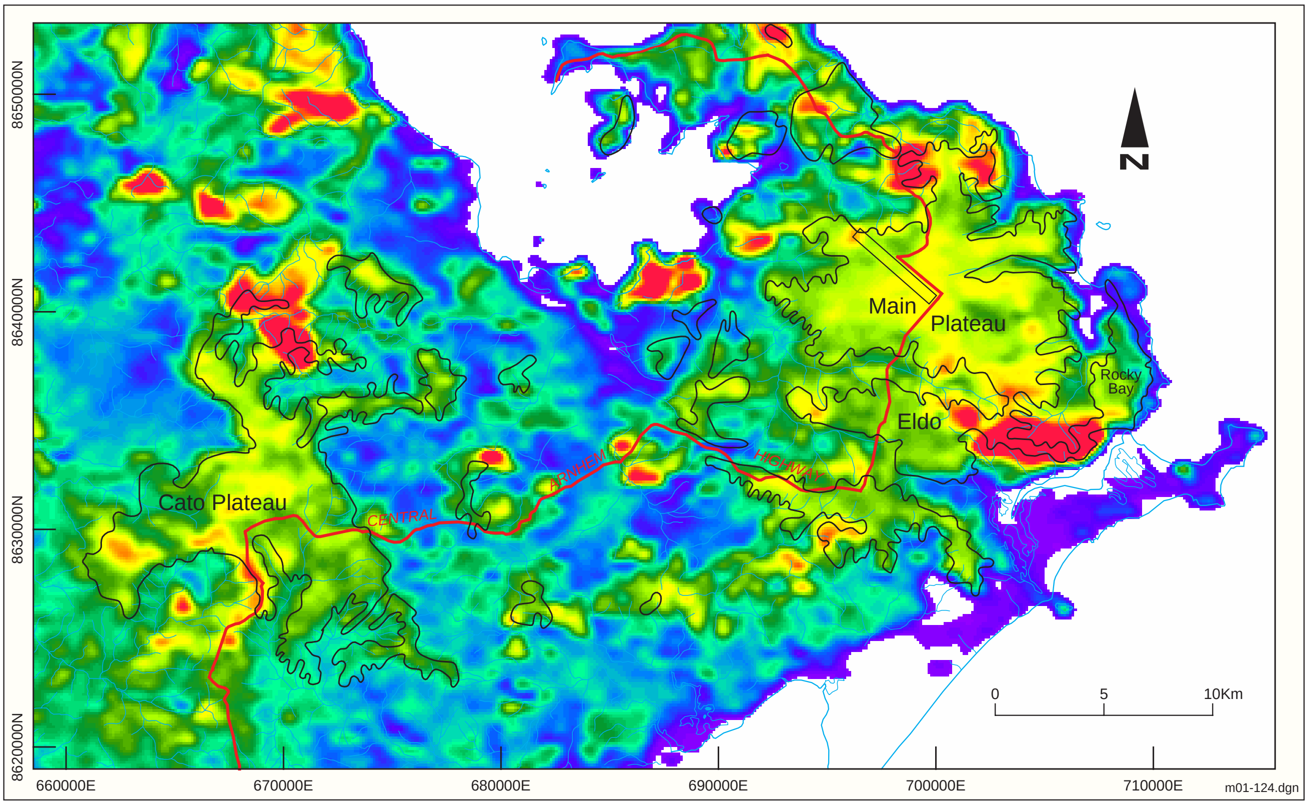

Figure 56. Thorium radiometric signature of Gove Peninsula

vertical and/or lateral drainage and oscillations of the groundwater table. A stable geomorphology enables cyclical, evolutionary weathering/concentration patterns over long periods. Simple reworking of bauxite material can occur on lowlands and plateaux that have irregular topography, so as to produce variations in the normal bauxite profile (eg at Gove).

Exploration and evaluation

The conditions and factors necessary for lateritic bauxite formation, as described above, provide important exploration criteria for broad target selection. For prospecting purposes, Bardossy and Aleva (1990) distinguished three deposit types:

1. Erosional remnants of originally extensive laterite-bauxite plateaux formed before the Middle Tertiary, eg Darling Ranges, Weipa and Gove;
2. As above, but covered by younger sedimentary deposits, eg the coastal plain of Suriname; and
3. Small Plio-Pleistocene deposits, eg Bintan Island, Indonesia.

Type 1 deposits include the majority of known commercial bauxite deposits. Prospecting for them essentially involves outlining plateau areas with pre-Middle Tertiary planation surfaces that, prior to that time, were located in a humid tropical climate zone. Type 2 deposits are hidden and require detailed regional geological analyses to locate them. Type 3 deposits are commonly found in very humid climates on porous feldspathic parent rocks within well drained morphological features (Bardossy and Aleva 1990). The following exploration methods mainly relate to Type 1 deposits but can also be applied to the other types.

Economic lateritic bauxite deposits are relatively large in bulk tonnage (>50 Mt). They occur at or near the surface and are essentially flat lying. This makes them a target of significant areal extent, compared to deposits of other commodities (eg Mn, Cu, Zn etc). Remote sensing methods that utilise satellite imagery, airborne geophysics, airborne hyperspectral mapping, aerial photography and digital terrain modelling can be used at a regional level.

Satellite imagery

Satellite imagery is used to define plateaux, drainage patterns and vegetation types. Henderson et al (1984) documented methods of exploration using LANDSAT MSS (Multi-Spectral Scanner) and LANDSAT TM (Thematic Mapper) data, and used several Australian bauxite deposits as examples. LANDSAT TM has the advantage of a middle infrared (2.08-2.35 mm) wavelength sensor (Band 7) that can map clay-rich areas. Iron oxide-rich areas can be identified using the visible red wavelength bands (Band 3 for TM).

Airborne geophysics

Airborne geophysics can detect radiation generated by minerals at the surface via radiometric sensors. Resistant radioactive minerals like zircon and possibly monazite and xenotime can accumulate in the laterite/bauxite profile in very small quantities. If present at the surface, these minerals generate radiometric Th and U anomalies. However, this method, does not discriminate between ore-grade bauxite and barren laterite (**Figure 56**). Medium to dense vegetation cover also reduces the effectiveness of this exploration tool.

Hyperspectral mapping

Hyperspectral mapping involves the collection of hyperspectral ground reflectance data from a conventional airborne geophysical platform (Hausknecht *et al* 2000) or satellite (eg JERS and ASTER). Commercial airborne sensors such as OARS (Operational Airborne Research Spectrometer), HYMAP, GEOSCAN and AMS (Airborne Multispectral Scanner) allow the identification of most species of phyllosilicates, clays, carbonates and iron oxides that occur in regolith and parent rocks. This technique has several advantages over satellite-generated data in that it has a higher signal to noise ratio, a higher pixel resolution (10 m compared to 30 m for TM), and more accurate integration with other geophysical data, because data acquisition is synchronous and geo-referenced. Spectra of common minerals found within the bauxite environment are shown in **Figure 57**. Note that the natural reflectance signatures of gibbsite and diaspore are similar but are lower than kaolinite, so that the use of ratios over selected bandwidths (eg difference between 0.5 µm and 1.2 µm) may be required to map bauxite minerals.

Aerial photography

Aerial photography can be used to map geological structures and lithologies, as well as important geomorphologic features such as planation surfaces, regolith and drainage.

Digital terrain models (DTM)

Digital terrain models (DTM) can be generated by a variety of methods, the most common being photogrammetry and satellite imagery (eg SPOT). Airborne geophysical and more specific airborne radar surveys (eg LIDAR) can also generate high quality DTM or digital elevation models (DEM) over relatively large areas. Airborne surveys are probably the most accurate and costly acquisition method. A DTM over a region with bauxite occurrences can identify nearby plateaux that have the same elevation as known occurrences and may therefore be prospective targets.

Regional follow-up work is required to verify the presence of bauxite and assess potential for economic quantities. Systematic sampling of natural outcrops is required to

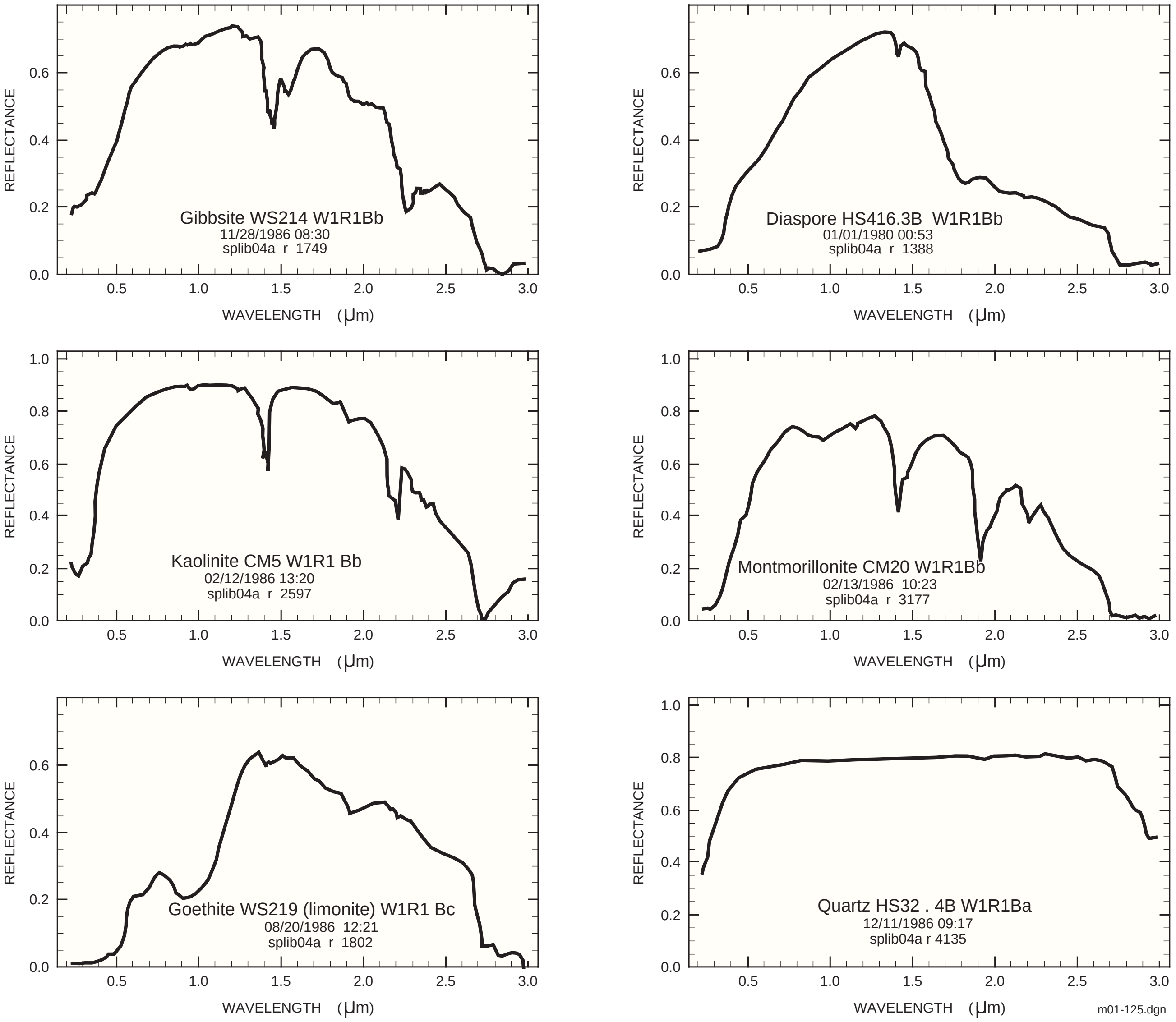

Figure 57. Spectra of common minerals found within the bauxite environment, from USGS digital spectral library (after Clarke *et al* 1993)

determine the quality of the material along strike and at various depths. Grid sampling is necessary if natural outcrops are limited. Before grid sampling is undertaken, a pit or costean might be excavated in the most prospective locality to determine the nature of the weathering profile and possibly the parent rock. Bardossy and Aleva (1990) have outlined numerous sampling methods and their effectiveness. Four-wheel drive, truck-mounted, uncased auger or vacuum drilling methods are fast, simple to use, relatively cheap and efficient in hilly, wooded terrains.

Reconnaissance drilling may start on a 3000 m (eg Aurukun prospect), 1000 m (eg Mitchell Plateau) or 400 m (eg Gove) square grid, depending on: 1) geological factors (eg expected ore and overburden thicknesses); 2) cost factors; 3) seasonal constraints (eg climatic conditions affecting access); and 4) the exploration strategy of the company. If the maximum thickness of an economic lateritic bauxite deposit is about 10 m, and if a minimum tonnage of 10 Mt is required, such a deposit (using an *in situ* SG of 1.5) would cover an area of 820 x 820 m. Therefore, a reasonable sampling grid might start with parallel lines at 400-800 m separation and sample intervals at 200-400 m, in order to provide a compromise between rapid progress and obtaining a reasonable geological model of the deposit (Bardossy and Aleva 1990).

Once the presence of economic bauxite is established, drill sampling can be reduced to a 200 m square grid for resource estimation, then to 100 m or 50 m for ore reserve estimation and mine planning, depending on ore quality variations. Alcoa Australia Ltd uses a 15 x 15 m sampling grid for grade control and monitoring at its Darling Range bauxite mining operation, in order to meet exacting refinery-grade specifications (Hickman *et al* 1992).

When assessing the economic potential of a deposit, a number of geological, mining, environmental and commercial factors require consideration (**Table 18**). In Australia, the JORC code (JORC 1999) sets out minimum standards and guidelines for public reporting of mineral resources and ore reserve estimations. Analytical assays of the bauxite, which commonly use XRF and bomb-digest tests, will quickly reveal whether exploration work should be abandoned or expanded. The quality of the bauxite can be determined by the amounts of available alumina (Av.Al_2O_3), reactive silica (Re.SiO_2), iron oxide (Fe_2O_3) and titanium oxides (TiO_2) present in the material.

Bauxite is typically classified according to its intended commercial use. It has metallurgical, chemical and refractory applications and may also be utilised as an abrasive or cement (**Table 19**). Andrews (1984), Bardossy and Aleva (1990, Chapter 8) and Hill (1994) provide comprehensive accounts that cover the uses of bauxite and its specifications. The following sections are essentially summarised from these publications.

Metallurgical grade

About 85% of mined bauxite is converted to alumina for the production of aluminium metal (Plunkert 2000a). Alumina is extracted from bauxite by a wet chemical caustic leach method, known as the Bayer refining process (see below). The main impurity in (metal-grade) bauxite is silica, which is present as *reactive silica* and as quartz. Reactive silica (Re.SiO_2) is the silica in silicate minerals such as clay (usually kaolinite). It combines with caustic soda to form an insoluble sodium silicate compound, which results in the loss of Al_2O_3 and the consumption of caustic soda. This increases costs and reduces Al_2O_3 recovery. Quartz (also known as free silica) is essentially non-reactive and does not cause loss of either Al_2O_3 or caustic soda in the refining process.

Iron and titanium oxides are other significant impurities. Iron is commonly in the form of goethite, but also occurs as hematite, lepidocrocite and rarely magnetite. Goethite is unpredictable during the alumina refining process, because its hardness depends upon its crystallinity and grain size (Hickman *et al* 1992). Goethite and hematite may contain Al as a substitute for iron and Al in goethite can be up to 45 mol%. These minerals are the main contributors to the red mud produced by the Bayer process. Most lateritic bauxite deposits contain 10-25% Fe_2O_3, but higher values have been recorded in deposits derived from mafic parent rocks (Bardossy and Aleva 1990).

According to Bardossy and Aleva (1990), anatase[4] (TiO_2) is usually present as fine disseminated grains throughout bauxite horizons in amounts of 1-10% (commonly 2-4%). Rutile (TiO_2) is also widespread but is usually present in trace amounts (<1%). Other trace resistate minerals include ilmenite, zircon, tourmaline, garnet and staurolite. Resistates generally pose no problems in the low temperature (140ºC) Bayer process. Organic carbon, if present, will react readily with caustic soda in the Bayer plant and bauxites with organic carbon levels >2% are undesirable.

The alumina content of bauxite is reported as total alumina (Al_2O_3) and available alumina (Av.Al_2O_3). The former reports the Al_2O_3 present in bauxite minerals, clays or aluminous iron oxides and is commonly determined by XRF. Most economic lateritic bauxite deposits will average 40-52% Al_2O_3 (Bardossy and Aleva 1990). Available alumina is essentially the alumina present as gibbsite, boehmite or diaspore and represents alumina that is readily extractable using the conventional Bayer process. It is commonly determined by a bomb-digest test. Most alumina refineries use bauxite that has an Av.Al_2O_3 content of 40% or more (Hickman *et al* 1992).

Gibbsite is the main alumina mineral of lateritic bauxites and generally forms 40-70 vol%. It is quite soluble in caustic soda and requires a digestion temperature of no more than 140ºC. Satisfactory levels of solubility of boehmite are normally obtained above 200ºC, whereas diaspore requires temperatures of greater than 300ºC (Andrews 1984). Boehmite and diaspore also need higher caustic soda concentrations and require more energy for grinding.

Chemical grade

Bauxite and alumina are the main components in the production of aluminium salts such as Al sulfate, Al chloride, Al fluoride and sodium aluminate. Aluminium sulfate (alum) is widely used as a flocculent in the treatment of domestic water supplies and effluents of various types. Bauxite can be used directly for alum production providing it consists

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[4] Also known as octahedrite.

GEOLOGICAL	MINING	ECONOMIC / ENVIRONMENTAL
Deposit(s): area, size (Mt), *in situ* dry density, thickness (min/max)	*Deposit(s):* number of separate deposits, range in size (area and Mt), distance (km) between each	*Infrastructure requirements*: power plant, housing, other workforce facilities (eg hospital, schools), workshops, loading facilities, roads, railway, airstrip, water supply, conveyor belts, etc
Overburden: thickness, composition	*Overburden:* Type, thickness (average, min/max), strength	*Energy costs*: mining operations, township, beneficiation plant
Grade in %: Av. Al_2O_3, SiO_2, Re. SiO_2, Fe_2O_3, TiO_2, C(org), LOI	*Physical character of ore*: hard, soft, brittle, tough, friable, loose, sticky, porous; blasting or ripping required	*Transport costs:* by trucks in mine, conveyor belts in mine and to plant, trains/trucks to refinery or loading facility
Grade distribution: horizontal and vertical variations, visual grade boundaries	*Beneficiation of ore*: breaking, crushing, grinding characteristics, washing characteristics	*Mining costs*: overburden removal, blasting, digging, loading, breaking, crushing. mine drainage, ore quality and environmental monitoring
Mineral composition: Al, Fe and Si minerals, and grain sizes	*Rainfall*: average per year, wettest and driest months	*Availability of*: beneficiation water, drinking water, red mud disposal area, overburden spoil area, topsoil storage area, ore stockpile area
Special grades: chemical, cement, refractory abrasive, tonnages of each *Beneficiation*: type and percent recovery (if required) *Terrain*: access for exploration equipment and personnel	*Distances between*: mine front – primary crusher, primary crusher – beneficiation plant, beneficiation plant – harbour, beneficiation plant – refinery *Terrain*: height of ore deposit (AMSL), level of water table	*General*: mine life of project, expected revenue from quality of bauxite ore, world price of alumina, native title issues, taxes and royalties, skilled labour force, mine site rehabilitation

Table 18. Aspects that determine the economic potential of a bauxite deposit (modified from Bardossy and Aleva 1990)

Grade	Al_2O_3	Av. Al_2O_3	SiO_2	Re.SiO_2	Fe_2O_3	TiO_2
Metallurgical	40-55	Min 30	Max 20	Max 6	4-30	Max 4
Chemical	Min 55		Max 12		Max 2	Max 4
Abrasive	Min 55		Max 7		Max 6	2-4
Refractory	Min 60		Max 10		Max 3	Max 4
Aluminous cement	35-55		Max 8		3-20	Max 2.5

Table 19. Chemical composition of typical raw bauxite grades (%). Source*:* Andrews (1984), Bardossy and Aleva (1990), Hill (1994)

essentially of gibbsite and has low levels of iron oxides (Al_2O_3/Fe_2O_3 ratio >20:1). Silica levels of 10% can be tolerated, but toxic ions and high levels of organic compounds must be avoided due to adverse affects on water quality.

Abrasive grade

Abrasive-grade bauxite is used for the production of fused alumina, a substitute for natural corundum, in the manufacture of grinding and polishing equipment (eg wheels and blocks etc). The raw bauxite is first calcined, which involves heating to 1000-1700°C to reduce the hydrous content from about 30% to <1%, or converted to alumina, before fusion is carried out in an arc furnace at temperatures of 2000°C or more (Andrews 1984). The alumina or calcined bauxite feed requires >80% Al_2O_3, <10% Fe_2O_3, <10% Si, low levels of alkalis (eg CaO) and water to maximise productivity and reduce impurities.

Refractory grade

Refractory materials that are used for bricks to line smelting and calcining furnaces (eg steel, nickel and alumina industry) require in excess of 45-50% alumina as a component of bauxite. The bauxite used must also have low Fe_2O_3, TiO_2 and trace amounts of alkalies and alkaline earths. Elements such as K, Na, Ca and Mg can form undesirable minerals with low melting points, whereas S, Cl and F should be avoided due to their highly corrosive activity during the calcination process. Some bauxitic material, which contains high levels of silica but low levels of other impurities, may be calcined to yield refractory grogs containing 50-70% Al_2O_3 and 25-40% SiO_2 (Andrews 1984).

Aluminous cements

Two types of aluminous cements are produced; these are referred to as low iron (calcium aluminate) and high iron (cement fondu) varieties. The raw materials are usually bauxite and limestone. Calcium aluminate cement is used as the refractory cement for bonding high alumina refractories. Cement fondu has applications in areas where structural strength must be developed within 24 hours and/or there is a requirement for high resistance from chemical attack (eg from salt water). Portland cement is generally a mixture of limestone and high alumina clay or shale. However, limited quantities of low-grade bauxite can be incorporated into the blend to produce a cement with a preferred silica modus ($\%SiO_2 / \%[Al_2O_3 + Fe_2O_3]$) of 2.6 to 2.8, with alumina greater than iron oxide (Andrews 1984).

Ore extraction and treatment - a summary

With the exception of a few small operations that are restricted to the production of non-metallurgical-grade bauxite, mining is generally carried out by large-scale surface methods (open pit). These typically extract 1-15 Mt/yr over a 20-40 year period (Bardossy and Aleva 1990). The mining operation at Gove is representative of the sequence and style of surface bauxite mining worldwide and a summary of this operation, based on O'Keefe (1993), follows.

The mining sequence starts with the removal of surface vegetation by a chain pulled between two Caterpillar D10N bulldozers. Topsoil and overburden is removed by scrapers and placed on the floor of mined-out areas that have been prepared for rehabilitation. In areas where loose pisolitic ore is >1 m in thickness, front-end loaders excavate the bauxite. Most of the bauxite ore (90%) is ripped-up and broken using D10N and D11N bulldozers, which collectively achieve an average productivity of 1400 dry t/h. Bauxite is mined at an average rate of 6.5 Mt/yr or 120 ha/yr and a similar area is rehabilitated.

Ore is loaded by 12.3 m^3 front-end loaders into 80 t rear dump trucks. Ore is removed at an average rate of 1000 t/h for the main deposit. At the Rocky Bay mine site, Kenworth 900 semi-trailers are used for hauling ore. The average haul distance is 4.7 km one-way for the main deposit and 10 km for the Rocky Bay deposit. Ore is crushed to a particle size of <25 mm at a rate of 1600 t/h, then transported via an 18.7 km-long overland conveyor system to the stockpile area, which is adjacent to the alumina plant.

Gove bauxite does not require beneficiation, but many other operations improve the quality of the run-of-mine ore to obtain a marketable product. A reduction in the reactive silica component is achieved by scrubbing and wet screening the ore after it is crushed, provided a significant proportion of the kaolinite occurs as loose, clay size (<4 μm) particles that are not intergrown with gibbsite. A lowering of the iron oxide content is often required to meet non-metallurgical bauxite specifications (eg for chemical and refractory grades). Optical sorting can be used for relatively small tonnage operations, whereas heavy-medium separation is more suitable for larger operations.

In nearly every commercial operation, alumina is extracted from bauxite by the Bayer refining process. Detailed descriptions of alumina production via the Bayer process are given for Gove by Gouma and Bhasin (1993), for Gladstone by Skiba (1993) and for the Darlings Ranges (Alcoa) by Debney (1993). The process essentially consists of four stages:

1. *Digestion*. Finely ground bauxite is fed into a steam-heated unit called a digester. In the digester it is mixed under pressure with a hot solution of caustic soda (140-150ºC for gibbsitic ores) and kept under pressure for 0.5-3 hours. The aluminium hydroxides and some of the kaolinite react with the caustic soda to form a solution of sodium aluminate (green liquor) and a precipitate of sodium aluminium silicate.

$$\underset{\text{(gibbsite)}}{Al_2O_3.3H_2O} + \underset{\text{(caustic soda)}}{2NaOH} + \text{heat} \rightarrow \underset{\text{(Na-aluminate)}}{2NaAlO_2} + 4H_2O \tag{1}$$

$$\underset{\text{(kaolinite)}}{Al_2O_3.2SiO_2.2H_2O} + \underset{\text{(caustic soda)}}{6NaOH} \rightarrow \underset{\text{(Na-silicate)}}{2Na_2SiO_3} + \underset{\text{(Na-aluminate)}}{2NaAlO_2} + 5H_2O \tag{2}$$

$$\underset{\text{(green liquor)}}{2NaAlO_2} + 4H_2O + \text{cooling} \rightarrow \underset{\text{(Na-Al silicate)}}{NaO_2.Al_2O_3.2SiO_2} + \underset{\substack{\text{(desilication}\\ \text{of liquor)}}}{4NaOH} \tag{3}$$

2. *Clarification*. The green liquor is separated from undissolved iron oxides (red mud) and silica (sand), which are pumped to residue ponds; the liquor is pumped to heat exchanges where it is cooled from 100ºC to around 70ºC.

3. *Precipitation*. Alumina is precipitated from the liquor as crystals of alumina hydrate when the liquor is mixed in tall precipitator vessels with small amounts of finely crystalline alumina (fine seed), which stimulates agglomeration as the solution cools.

$$2NaAlO_2 + 4H_2O + \text{cooling} \rightarrow 2NaOH + Al_2O_3.3H_2O \tag{4}$$

4. *Calcination*. The solid alumina hydrate (artificial gibbsite) is washed and dried, then heated to about 1100ºC to drive off the water of crystallisation. This leaves a dry, white sandy alumina product.

$$\underset{\text{(pure gibbsite)}}{Al_2O_3.3H_2O} + \text{heat (1100ºC)} \rightarrow \underset{\text{(pure alumina)}}{Al_2O_3} + 3H_2O \tag{5}$$

Homogeneous batches of bauxite are required for this process. About 5 t of bauxite and 160 kg NaOH are required to produce 2 t of alumina. A schematic flow sheet for the production of alumina at Gove is shown in **Figure 58**. For bauxite with either a high iron or high silica content, several processes (eg the Pedersen process) have been developed and these involve sintering the ore with lime-containing additives (Bardossy and Aleva 1990).

Aluminium is normally produced by the Hall-Heroult smelting process, which involves separating the aluminium and oxygen in alumina by electrolysis. The process consists of passing an electric current through a molten solution of alumina and cryolite (Na_3AlF_6) or aluminium fluoride (AlF_3) at 950–970ºC. The molten solution is contained in reduction cells (pots). These are lined with carbon (the cathode) at the base and are connected in an electrical series (potline). Consumable carbon anodes are inserted into each pot from above.

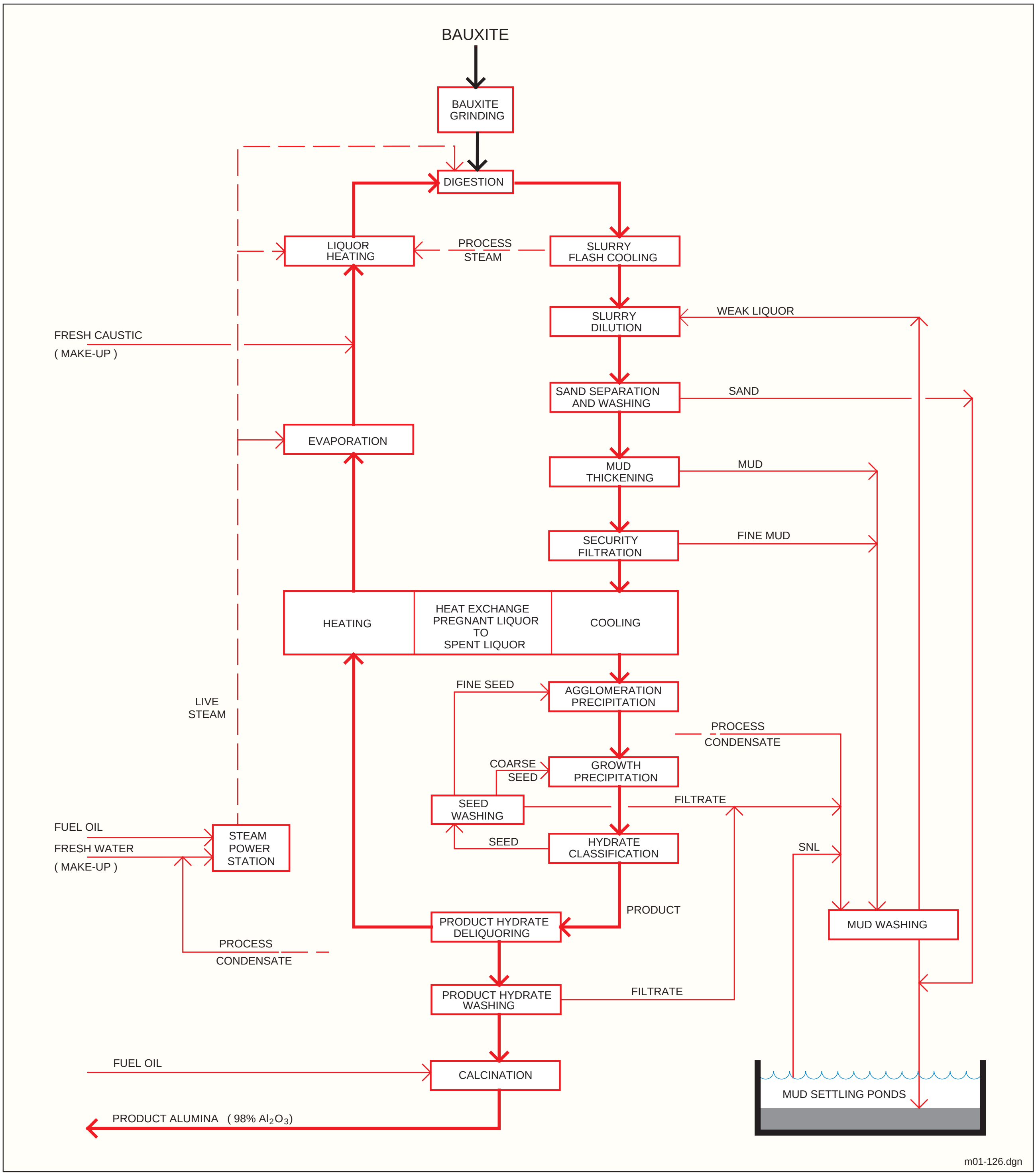

Figure 58. Schematic flow sheet for the production of alumina at Gove (after Gouma and Bhasin 1993)

The passage of the electric current causes oxygen from the alumina to combine with carbon at the anode to form carbon dioxide gas as molten metallic aluminium collects at the cathode. The simple chemical reaction is:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2 \text{ (Hall-Heroult process)} \qquad (6)$$

Molten aluminium is periodically tapped from the pots by ladles and transported to the cast house or holding furnace where impurities are removed and alloying elements (eg Mg, Si, Mn) are added, before it is cast into various forms. A large amount of energy is consumed during the smelting process; 14-16 000 kilowatt hours of electrical energy is required to produce 1 t of aluminium from 2 t of alumina.

The following publications are recommended for further information: for general aluminium production and the uses of aluminium, see Altenpohl (1998); for the Australian aluminium industry, see AME (1992) and ACIL (2000); for world bauxite and alumina, see Plunkert (2000a); and for world aluminium, see Plunkert (2000b).

BAUXITE DEPOSITS OF THE NT

Bauxite exploration and mining in the NT

Bauxite was discovered in the Northern Territory at Mount Roe on the Cobourg Peninsula by HYL Brown in 1907. In 1949, a BMR geologist, HB Owen, investigated this discovery and in the same year, the Northern Territory Coastal Patrol Service collected specimens of bauxite from Truant and Marchinbar Islands to the north of Gove. These samples were forwarded to Owen. Several small deposits that are located on Marchinbar Island were tested by the Australian Aluminium Production Commission in May 1952 (Owen 1953). While this work was proceeding, the Northern Territory Coastal Patrol Service collected a specimen of pisolitic bauxite that contained 52.6% Al_2O_3 from near Gove airstrip. This led to a more detailed reconnaissance and assessment of the Gove deposit by Owen in August 1952. All attention was subsequently directed to this area instead of Marchinbar Island.

Between 1953 and 1964, several companies explored the special mining leases at Gove and other prospective areas on the Cato Plateau. Eventually in 1965, Nabalco Ltd were given an opportunity to explore and develop the bauxite deposits at Gove. Following a feasibility study in 1968, Nabalco proposed a $1.5 bn bauxite-alumina project that was subsequently approved by the Federal Government. The project involved the establishment of a 6 Mt/yr open cut mine, an 18.7 km ore conveyor system, an alumina refinery, a modern town (Nhulunbuy) and a port. Mining commenced in 1971 and the alumina plant was commissioned in 1972.

Past production of bauxite and alumina at Gove is given in **Figure 59**. In 2000/01, about 6.7 Mt of bauxite grading 49.1% Al_2O_3 was mined, of which 2.2 Mt was exported and 4.5 Mt was refined to produce 1.8 Mt of alumina. As of March 2001, a remaining Total Reserve of 176 Mt grading 51% Al_2O_3 will provide for a mine life of 27 years, at current mining rates.

Reconnaissance exploration by various companies between 1957 and 1965 across the northern coastline of the Northern Territory identified small bauxite deposits on Croker Island, Cobourg Peninsula and Western Melville Island. Follow-up work on these deposits has indicated that the bauxite material is high in reactive silica. Exploration efforts over areas to the west of the Gove Peninsula (Chesnut *et al* 1966 and 1968) failed to identify any significant deposits in lateritic material overlying Cretaceous strata.

Some reconnaissance exploration for lateritic bauxite has been carried out by various companies along the southwestern NT coastline, and Daly River, Victoria River and Dry River areas with little success. A tabulation of bauxite occurrences and resource estimations is presented in **Appendix 3**.

Lateritic deposits

There are 27 recorded lateritic bauxite occurrences in the Northern Territory. These are located along coastal areas within the Carpentaria, Arafura and Money Shoal Basins (**Figure 2**). Deposits are preserved on stable plateaux that allowed deep bauxitisation during the Tertiary. Parent rocks are predominantly Cretaceous in age although this is not readily apparent on Marchinbar and Elcho Islands. Available information on the deposits is variable and mostly outdated.

Carpentaria Basin

Gove

On the Gove Peninsula in northeastern Arnhem Land, extensive lateritisation during the Tertiary has produced a world class bauxite deposit. Defined bauxite resources cap Cretaceous erosional plateau remnants and occupy an area of about 63 km^2 (**Figure 60**).

Mining commenced in 1971 and about 155 Mt of bauxite grading 50.5% Al_2O_3 has been produced to July 2001. A description of the mining process at Gove is given in the preceding section. The management company for the operation is Nabalco Pty Ltd, a wholly-owned subsidiary of Alcan Aluminium Ltd. The Gove refinery uses the Bayer process to produce sandy alumina (98.3% Al_2O_3) and has produced some 53 Mt (to July 2001) since the refinery was commissioned in 1972.

Exploration and Development

Following a brief investigation of the Gove deposit by the BMR (Owen 1952), a more comprehensive assessment was conducted in 1955 by the New Guinea Resources Prospecting Company[5], that included some 132 hand auger holes over the SML No1 area (Gardner 1955, 1957). In 1958, SML No1 was granted to the Commonwealth Aluminium Corporation Ltd[6] and a further 175 holes were drilled (Mead 1963).

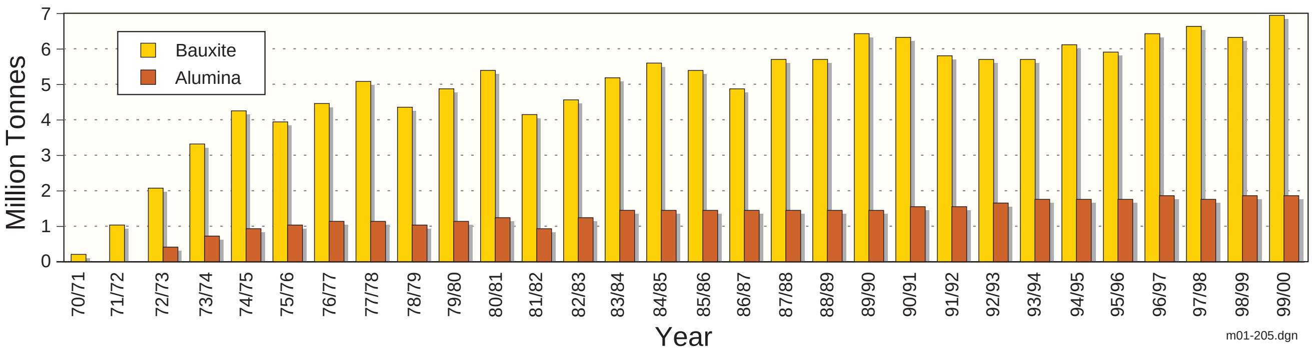

Figure 59. Past production of bauxite and alumina in the Northern Territory

[5] 51% Commonwealth Government and 49% British Aluminium Ltd.

[6] 50% British Aluminium Ltd and 50% Consolidated Zinc Ltd.

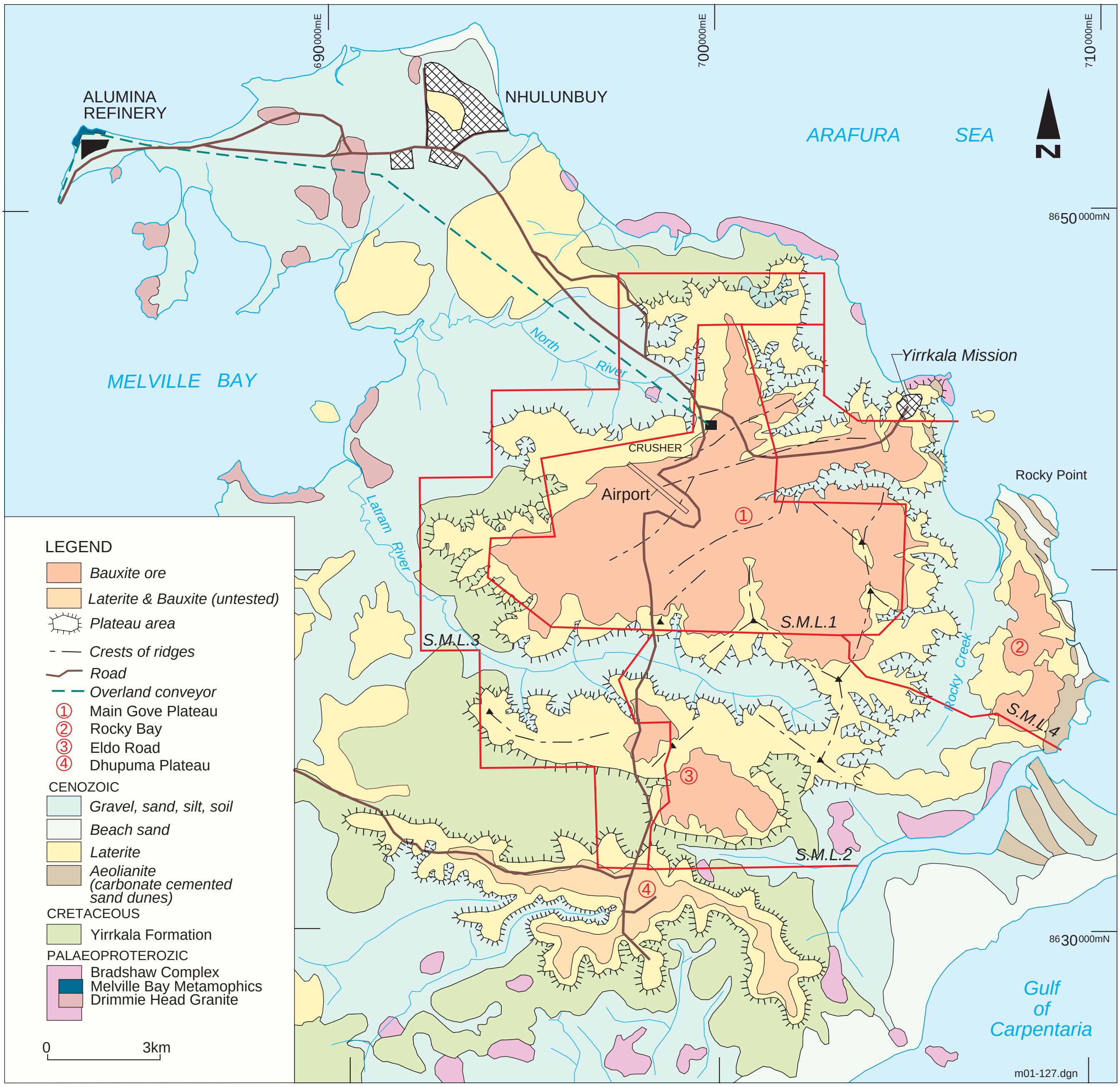

Figure 60. Simplified geology of Gove bauxite deposits (modified from Somm 1975, Rawlings *et al* 1997)

SML No1 was transferred to British Aluminium Ltd after Consolidated Zinc Ltd withdrew from Commonwealth Aluminium Corporation Ltd. In 1961, Gove Bauxite Corporation Ltd[7] was granted leases (SML's 2, 3 and 4), which surrounded SML No1. These leases were transferred to Gove Mining and Industrial Corporation (GOMINCO), which carried out a drilling program between 1962 and 1964 (Dickinson 1962, Sabot 1965).

Project proposals by British Aluminium Ltd in 1963 for SML No1 and GOMINCO for SML's 2, 3 and 4 in 1966 did not meet Government expectations and resulted in the leases being terminated. SML No1 was granted to Nabalco Ltd in 1965. Some 5450 drillholes totalling 26 000 m were drilled over a two year period (from April 1966) to determine the amount and grade of minable bauxite (Lillehagen 1979). This was part of a comprehensive feasibility study that led to the Government approving a massive mining project, which involved a 1 Mt/yr alumina plant and the export of bauxite at a rate of 2 Mt/yr.

Drilling commenced on a square 100 m grid, but spacing was increased to 200 m, in order to accelerate the evaluation program. This extended grid gave a statistically acceptable level of confidence in the ore reserve figure. Perimeter regions (SML's 2, 3 and 4) were initially drilled on a 400 m grid, then on a 200 m grid after the presence of ore-grade bauxite was identified. Drilling was carried out using truck-mounted drill rigs with 15 cm diameter rotary sample barrels. Samples were taken in half-meter intervals and quartered in the field, then

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[7] A subsidiary of Duval Holdings Ltd.

later combined to 1 m composites for laboratory analysis (Nabalco 1968a). Samples were analysed by XRF methods for Al_2O_3, Fe_2O_3, SiO_2 and TiO_2 at the Alusuisse research facilities in Neuhausen, Switzerland. Quartz and LOI were determined in the laboratory at Gove.

Due to the various bauxite ore types at Gove, pilot mining was necessary to assist in optimum process design for the alumina plant. Three parcels of ore (642 t, 2450 t and 1050 t) were shipped to a pilot plant in Venice, Italy. The original bauxite ore reserve within SML No1, before mining commenced, was 253.75 Mt grading 50.4% Al_2O_3 and 4.1% SiO_2. This estimate used cut-off values of <5% SiO_2 and >44% Av.Al_2O_3 and an ore depth of at least 1.8 m or 1.2 m, where the stripping ratio is <1.5:1 (Lillehagen 1979). The 'area of influence' method was used for this estimation. A later computer-assisted estimate by Lillehagen (1979) gave an estimate of 282.02 Mt grading 51.1% Al_2O_3 and 4.2% SiO_2. This estimate used cut-off values of <8% SiO_2 and >40% Av.Al_2O_3 and an ore depth of at least 2.0 m or a stripping ratio of <1.5:1.

Grade control drilling on a 50 m square grid is required to provide analytical information for daily planning. The maximum allowable grade variation in ore feed for the refining plant is 0.25% Av.Al_2O_3 in any one hour; hence the need for selective mining and ore blending. Reconciliation of computed reserves against actual tonnage mined to the end of 1985 gave the following results (Bardossy and Aleva 1990): computed - 60.8 Mt grading 50.8% Al_2O_3 and 3.4% SiO_2; actual - 60.8 Mt grading 50.1% Al_2O_3 and 3.22% SiO_2.

Geological Setting

Basement rocks in the area (**Figure 60**) form part of the Arnhem Inlier. They comprise Palaeoproterozoic (ca 1870 Ma) pelitic, calcsilicate, psammitic and mafic gneiss, and migmatite and garnetiferous leucogranite of the Bradshaw Complex (Rawlings *et al* 1997). Diamond drilling (Dodson 1967) and geological mapping indicate that there is a 100-200 m thick succession of gently dipping, Lower Cretaceous sandstone and claystone (Yirrkala Formation) unconformably overlying the Bradshaw Complex.

Beneath the laterite profile at Gove, the Yirrkala Formation consists mainly of friable, kaolinised, fluvial arkosic sandstone and quartzose sandstone that is interbedded with minor claystone. The claystone contains lignitic coal partings (Dodson 1967), which have yielded a Late Albian (ca 100 Ma) microflora (Evans 1967). Beneath the laterite at Rocky Point, weathered shale of the Yirrkala Formation dips at 20° to the north-northeast.

Bauxite profiles and characteristics

The following description is based on publications by Grubb (1970), Plumb and Gostin (1973), Somm (1975), numerous discussions with Dan O'Keefe (former Nabalco Mine Manager) and a field visit to the mining area in July 1997.

The main plateau hosting the Gove deposit is gently undulating and is typically 30-60 m ASL (**Figure 61**). Water table depth is about 30 m below the plateau surface. For mining and exploration purposes, three separate bauxite orebodies have been identified; these are referred to by Nabalco Ltd as the Main Gove Plateau (mainly in SML 1), Rocky Bay (SML 4) and Eldo Road (SML 2 and 3) deposits.

The thickness of the bauxite sheet in the Main Gove Plateau deposit averages about 3.7 m, and ranges from absent at plateau edges and on hill crests to 10 m in topographic swales (**Figure 61**). Up to eight layers are recognised in the normal or complete laterite profile (**Figure 62**); these are, from top to bottom:

- topsoil;
- loose pisolitic bauxite (LP);
- cemented pisolitic bauxite (CP);
- tubular bauxite (Tub);
- lower nodular bauxite (LN);
- nodular ironstone;
- mottled zone; and
- saprolite.

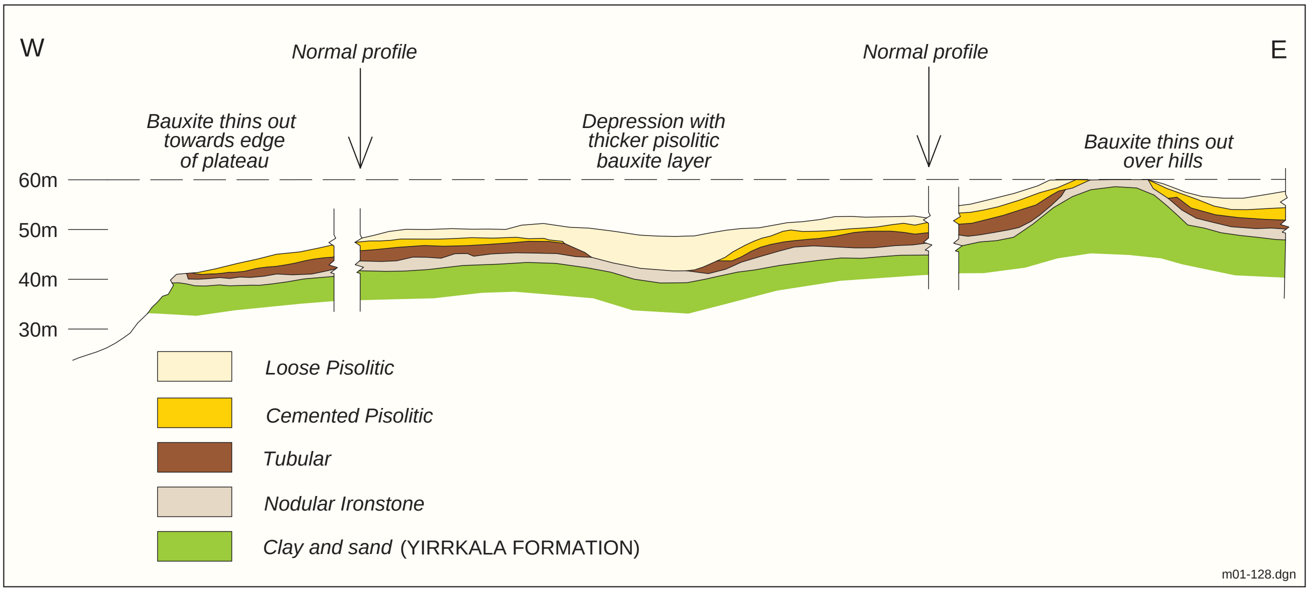


Figure 61. Schematic cross section of bauxite deposit on Main Gove Plateau (after Lillehagen 1979)

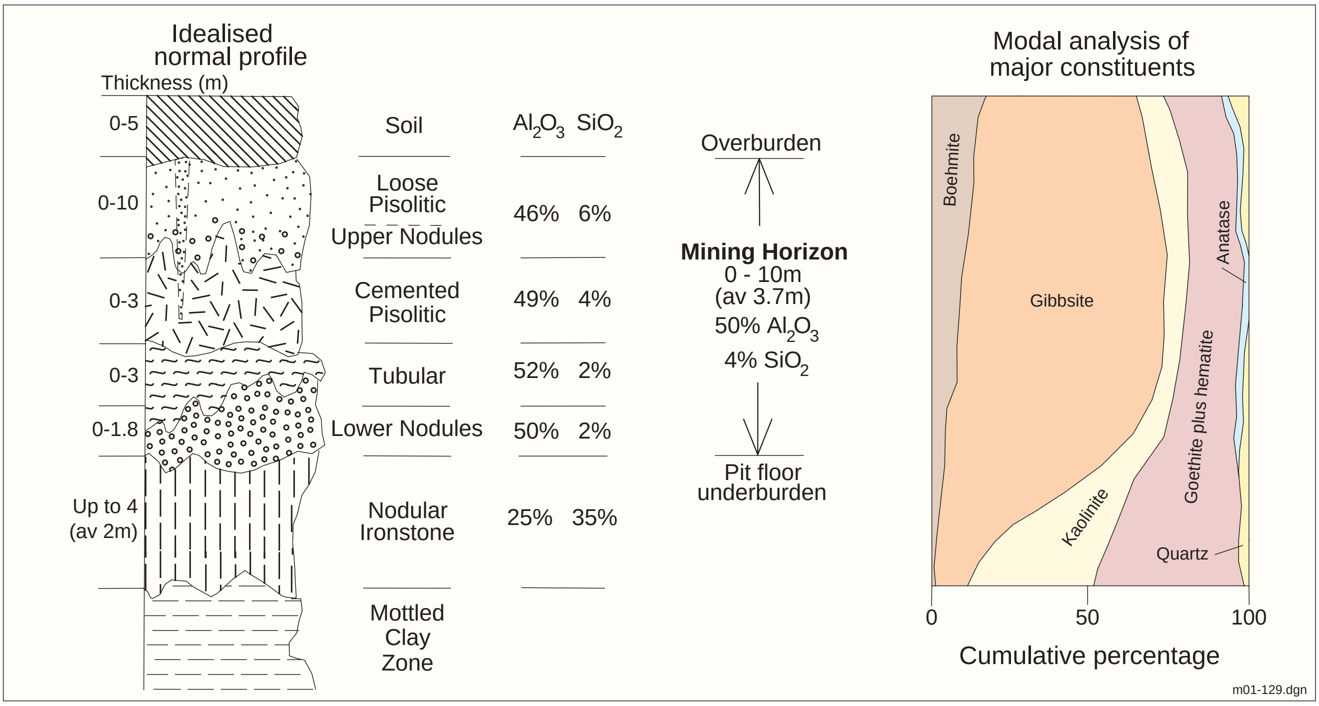


Figure 62. Generalised bauxite profile at Gove (modified from Grubb 1970, Somm 1975)

Topsoil is composed of red-brown clayey loam that contains scattered fragments of bauxite and organic remains. Its thickness varies from 0-5 m and averages about 0.8 m.

Loose pisolitic (LP) bauxite ore is up to 10 m thick and averages about 3 m. It typically consists of rounded reddish-brown pisoliths, which are 0.7-15 mm in diameter (commonly 3-6 mm). These are loosely cemented in a fine red matrix that consists of angular quartz grains, laterite fragments, bauxite grains and broken pisolith shells. Root structures are common (**Figure 67**). Hard, concretionary nodules, which are up to 60 mm in diameter, are often present in the lower parts. The basal contact is generally sharp and is highly irregular.

Cemented pisolitic (CP) bauxite ore is up to 3 m thick and averages about 1.5 m. It consists of densely packed pisoliths (as per LP bauxite ore) that are cemented in a reddish or creamy matrix. Root structures and bauxite nodules are also present. The degree of cementation is variable; soft CP ore fractures around the pisoliths and brittle CP ore fractures across the pisoliths. Sections of brittle CP ore (**Figure 63**) show the characteristic concentric structure of the pisoliths. The lower contact of this layer is generally sharp and gently undulating.

The *tubular bauxite (Tub)* layer is up to 3 m thick and averages about 1.5 m. It is well cemented, reddish-brown, massive, and contains irregular anastomosing vesicular cavities (**Figure 64**). The massive part of the rock is composed of loosely packed pisoliths that have been replaced by dense, amorphous red-brown cement. Solution cavities and pedotubules are lined with a creamy-yellow coating and are commonly infilled with complete or hollow pisoliths in a hard creamy cement. Toward the top of this layer, cavities contain cemented pisoliths that are identical to those in the CP layer.

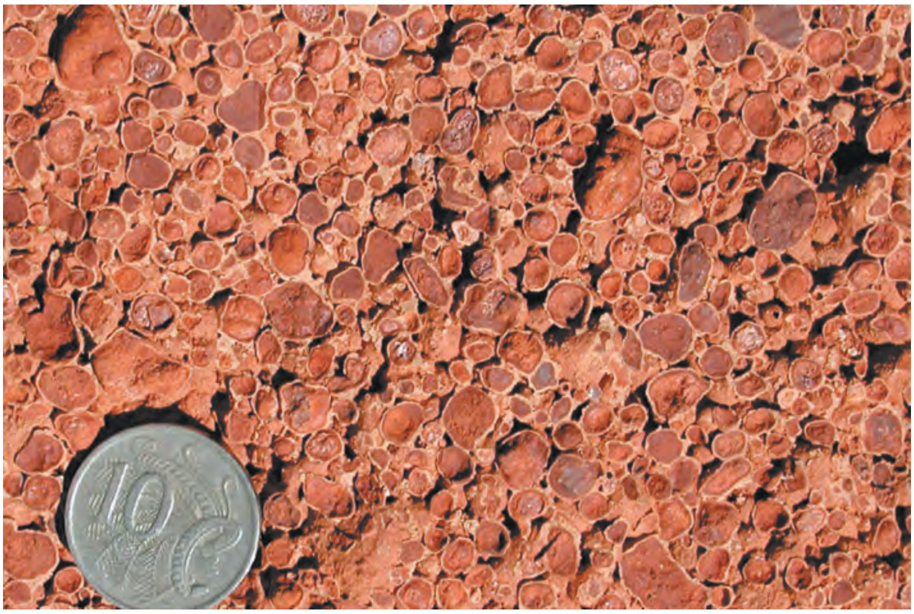


Figure 63. Characteristic concentric structure of pisoliths in CP ore from central area of Main Gove Plateau

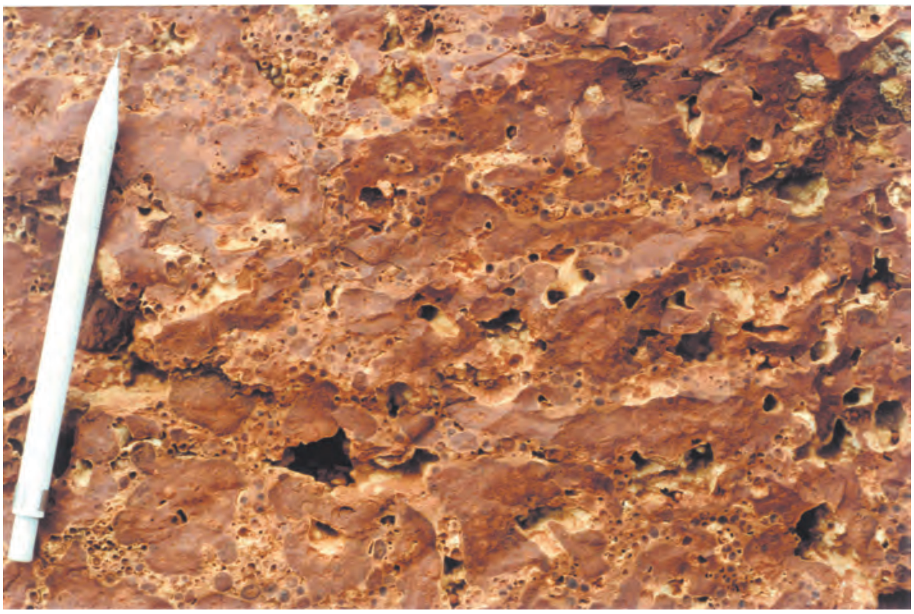


Figure 64. Tubular bauxite (Tub) ore from central area of Main Gove Plateau (pen length is 14 cm)

A crude sub-horizontal or vertical orientation of the cavities can be observed in places. Tub ore is consistently lower in silica (av 2% SiO_2) and higher in alumina (53% Al_2O_3) than CP ore (4.5% SiO_2, 49% Al_2O_3).

Lower nodule (LN) ore is up to 1.8 m thick and averages about 0.3 m. It may substitute for Tub ore in places. This layer consists of very loosely cemented, subspherical to ellipsoidal, creamy-orange nodules that range in size from 5-30 mm. Nodules may be solid or hollow and commonly have cores containing one or more pisoliths. The contact between Tub ore and LN ore is usually regular and sub-horizontal, but blocks of the former can be observed in the lower nodule layer.

A porous, massive, *nodular ironstone* unit, which is up to 4 m thick, underlies the bauxite-bearing layers. It consists of variably cemented, loosely packed ferruginous (goethite and hematite) nodules and angular ferricrete fragments in an orange-brown clay matrix. This matrix has been extensively removed, so as to create irregularly spaced voids and vermicular cavities (**Figure 65**). The contact with the underlying mottled zone is irregular and sharp.

The *mottled zone* consists of kaolinitic clay that has irregular subhorizontal pink to reddish stains. It extends below the nodular ironstone unit and is well exposed along coastal cliff sections to the south of Rocky Point (**Figure 66**). Bands and nodules of ironstone are common in the upper parts. Layers of sand and shale relicts are present in the lower sections. The contact with the underlying saprolite zone is gradational.

The *saprolite* zone at Gove is essentially a 1-3 m thick kaolinite clay unit. It contains relict bedding structures and weathered shale bands, brecciated tabular fragments or blocks.

Incomplete bauxite profiles also occur. These are essentially eroded variations of the normal profile, where, for example, the LP and/or parts of the CP layer are removed, so as to leave a thinner bauxite ore section (**Figure 61**). A soft pisolitic-nodular profile (SPN) is present in the southeast portion of the main deposit and this essentially consists of up

Figure 65. Nodular ironstone from central area of Main Gove Plateau (hammer head length is 18 cm)

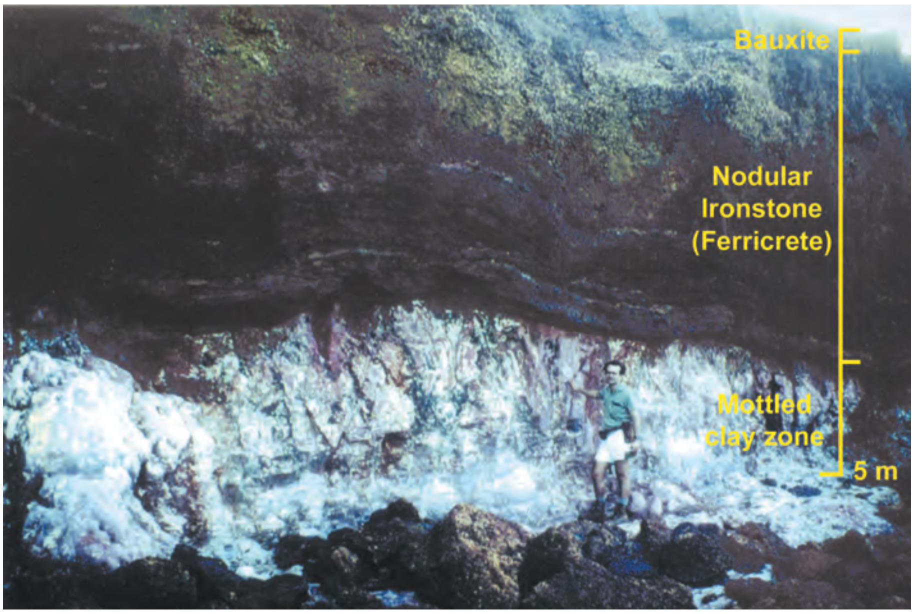


Figure 66. Mottled clay zone in cliff section south of Rocky Point at Gove

to 10 m of LP ore within a very fine, cohesive, creamy bauxitic-clay matrix. Pisoliths show graded bedding and a decrease in packing density towards the base, where the matrix becomes dominant. This ore is characterised by high alumina (53-58%), high silica (5-8%) and low iron (6-10% Fe_2O_3) contents.

In most of the quarry faces, pipe-like vertical root channels (**Figure 67**) and inverted steep conical structures can be seen penetrating bauxite layers from the surface. These pipes usually only extend through the LP ore layer and terminate at the CP ore contact. However, in some cases, they penetrate down into Tub ore and in places where the upper layers of the profile have been eroded, they penetrate whatever layer is near the surface. Root structures often contain root remnants and are filled with bauxite pisoliths (as per LP ore) in a sandy earthy-brown matrix. This material contains more silica (mainly as quartz grains) and less alumina than the surrounding bauxite ore. A hard cemented rim generally surrounds the cavity of the pipe. Bauxite (mainly LP ore) adjacent to the column is often bleached.

The bauxite is mainly composed of gibbsite and minor boehmite, particularly in the upper levels of the profile (**Figure 62**). Hematite and goethite are the iron oxide constituents of ore-grade material. The Fe_2O_3 content varies over the deposit from 8-23% and typically averages about 17%. According to Grubb (1970), there is a tendency for hematite to increase relative to goethite towards the top of the profile. Iron may also occur in clay minerals and in heavy minerals such as ilmenite or magnetite.

Silica is present as quartz (average 0.8%) and in kaolinite (average 3.3%). Quartz is more common in the upper 2 m of the profile, where it averages 2-3%. Kaolinite forms the bulk of the total silica in the bauxite ore (80%), which averages about 4% SiO_2. Silica levels increase to 35% in the nodular ironstone layer and this is due to increases in kaolinite content (**Figure 62**), as quartz remains at 0.7%. Titanium oxides average about 3.2% and are present in the form of anatase, although there are trace amounts of zircon and ilmenite. Combined H_2O (LOI) constitutes a significant proportion of the bauxite ore (average 26%) and is associated with Al- and Fe-hydrates, clay minerals and organic material.

An isoquality map for the Main Gove Plateau deposit (**Figure 68**) outlines an irregular distribution of low- and high silica bauxite. However, some topographic control is evident in the southwestern portion of SML 1, where a thick (>6 m) lens of high-silica bauxite lies between two northwest-

Figure 67. Pipe-like vertical root channels in central area of Main Gove Plateau (hammer length is 0.4 m)

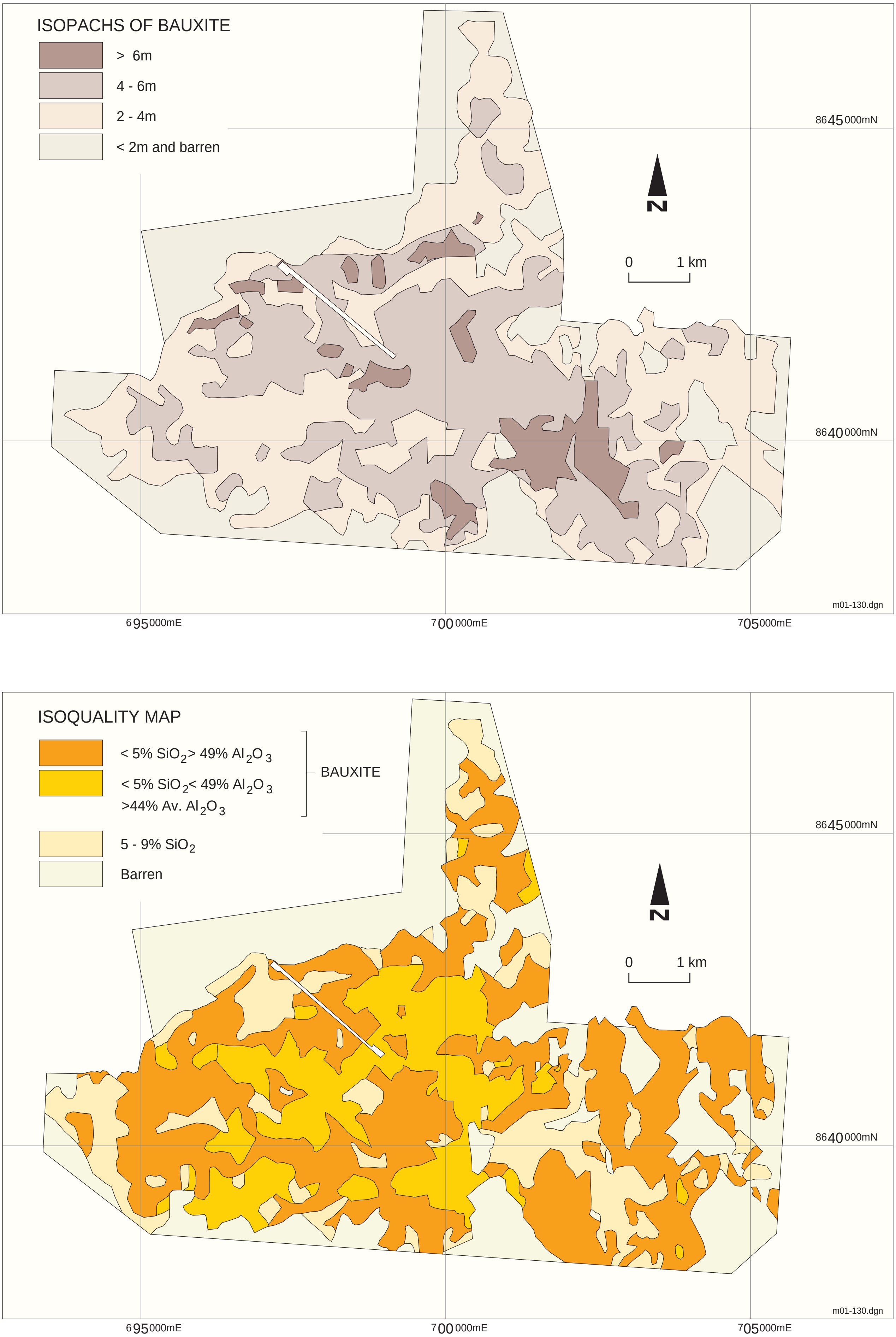


Figure 68. Isopach and isoquality maps of Main Gove Plateau (after Lillehagen 1979)

trending ridges. This probably represents a depression that has been infilled with transported pisolitic (LP) bauxite (see **Figure 61**).

Rocky Bay

Rocky Bay is separated from the Main Gove Plateau deposit by Rocky Bay Creek and covers an area of 9 km^2 (**Figure 60**). Initial drilling on a 300 m square grid by Gove Bauxite Corp (later GOMINCO) between 1962 and 1964 outlined about 17 Mt of bauxite grading 50.4-52.8% Al_2O_3 and 4.4-4.8% SiO_2. Gove Bauxite Corp estimated the average thickness of the deposit to be 3.35 m (Sabot 1965).

Nabalco Ltd re-drilled the entire deposit in 1966 on a 200 m square grid and defined a total reserve of 18.7 Mt grading 50.5% Al_2O_3 and 5.1% SiO_2, at an average thickness of 2.61 m (Nabalco 1968b). They determined the average free silica content of the ore to be about 2.5%. This reserve estimate includes a lower silica resource of 10 Mt @ 51.7% Al_2O_3 and 3.8% SiO_2. Mining of this deposit commenced in January 1996 and a 20 year mine life has been estimated. Ore is hauled to a stockpile, which is located 10 km to the west of the deposit, from where it is transported by conveyor to the Gove refinery.

Eldo Road

Eldo Road lies on a plateau to the south of the Lantram River (**Figure 60**). Drilling by Nabalco Ltd on a 200 m square grid (initially 400 m) has delineated a small northern (Eldo Road North) bauxite deposit and a larger southern (Eldo Road South) deposit.

Eldo Road North contains up to 6.2 Mt at 50.4% Al_2O_3 and 7.0% SiO_2. The deposit has an average thickness of 2.77 m and includes a low silica resource of 0.75 Mt @ 52.2% Al_2O_3 and 4.2% SiO_2. Free silica content of the Eldo Road ore averages about 2.5% (Nabalco 1968b).

Eldo Road South contains 20.4 Mt @ 50.9% Al_2O_3 and 6.4% SiO_2 and has an average ore thickness of 4.42 m (Nabalco 1968b). It includes a low silica resource of 7.9 Mt @ 51.9% Al_2O_3 and 4.1% SiO_2.

Dhupuma

Dhupuma is on an irregular narrow plateau, located 21 km to the south of Nhulunbuy. It is outside the Nabalco mining leases (**Figure 60**) and is within the Arnhem Land Aboriginal Land Trust. The elevation of the plateau is 80-100 m ASL and this is about 20-40 m above the main Gove Plateau. Grubb (1970) outlined a bauxite deposit that covers an area of 11 km^2 (**Figure 69**), but more recent geological mapping by NTGS (Rawlings *et al* 1997) indicated that about 5 km^2 of bauxite material is present. A section measured by Grubb (1970) near the Central Arnhem Road revealed a 3 m (9-10 ft) bauxite horizon composed of LP and CP ore (**Figure 70**).

Some 55 water boreholes have been drilled in the central portion of the plateau (**Figure 69**) and these have intersected a bauxite layer that ranges between 3.5 m (RN8252) and 11 m (RN4981) in thickness. Note that RN8252 and RN4981 are about 100 m apart, so it is possible that the significant

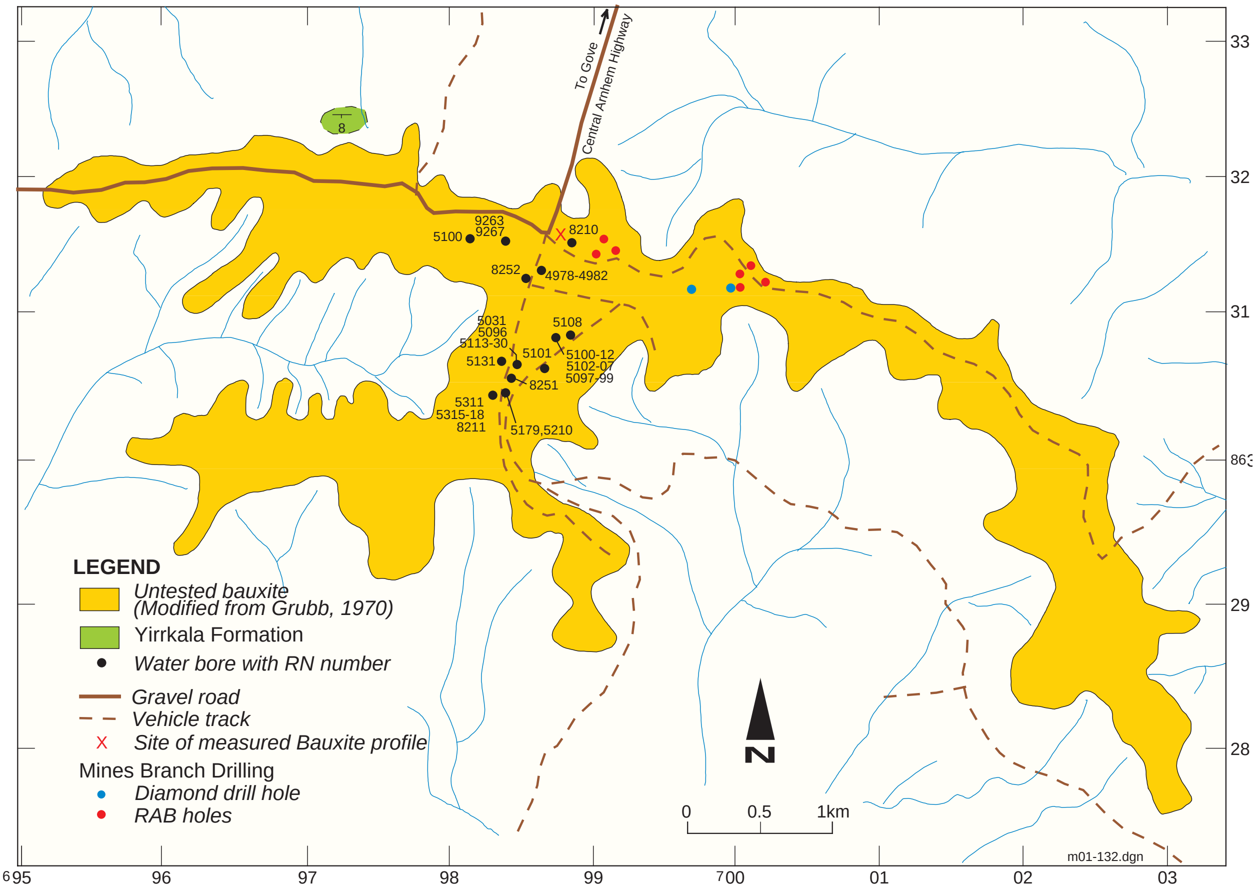


Figure 69. Dhupuma bauxite deposit

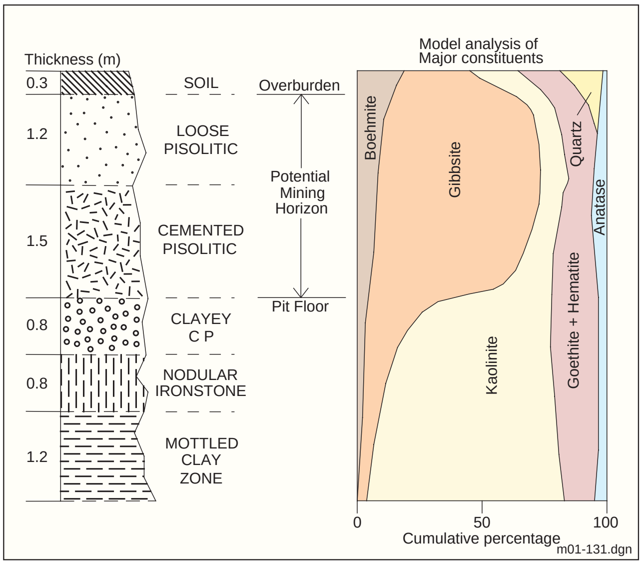


Figure 70. Bauxite profile at Dhupuma (modified from Grubb 1970)

thickness variation between these holes may reflect poor drillhole recovery or logging. Most of the holes (80%) intersected a 6.5-9 m thick bauxite layer. Borehole RN5210 penetrated a 0.6 m thick ironstone unit below the bauxite horizon and an underlying 88 m thick sand and clay succession (Yirrkala Formation), before reaching granite basement (Bradshaw Complex) at 97 m depth.

Seven RAB and two diamond holes (**Figure 69**) were drilled by the NT Mines Branch in 1964 to determine foundation conditions for antenna sites associated with the European Launcher Development Organisation (ELDO) station project (Hickey 1987). The seven RAB holes intersected an interval of weakly cemented pisolitic bauxite, 1.8-4.3 m in thickness (average 3.2 m), and all were terminated in an underlying tubular bauxite unit. Sample records indicate that diamond drillhole DDH 3 intersected at least 4.1 m of tubular bauxite (Hickey 1987).

Some analyses from samples obtained from three water bores are given in **Table 20**. These results indicate that 2-4 m of ore-grade bauxite material exists in some intersections. If further drilling is able to establish ore continuity over the entire 11 km^2 area, then potential for 35-70 Mt of bauxite-bearing material exists.

Cato Plateau

The Cato Plateau is located 32 km to the southwest of Nhulunbuy in northeastern Arnhem Land. It is about 100 km^2 in area, 90-150 m ASL and dips very gently to the south (Gardner 1957). The bauxitic laterite overlies friable sandstone and shale of the Yirrkala Formation.

The coarse pisolitic and tubular bauxitic laterite averages 3 m in thickness. It overlies a 3-10 m thick massive ferricrete horizon and is best developed over shale parent rock (Owen 1953, 1954). Waterbore RN26530, which was collared next to the road in the southern part of the area, intersected 84 m of coarse, friable clayey sandstone and sandy clay. Small exposures of basement Giddy Granite have been mapped to the east of the plateau near the Central Arnhem Highway (**Figure 71**).

In 1952, the Aluminium Commission conducted initial surface sampling of the prospect (Owen 1953). Two natural sections were measured and sampled. An attempt to sink a sampling pit failed due to hard ground conditions. Assay results were not encouraging; the best sample (0-1.8 m on the cliff section) returned 32.0% Av.Al_2O_3 and 12.3% Re.SiO_2.

In 1955, New Guinea Resources Prospecting Ltd, which was evaluating the Gove deposit, drilled 19 auger holes into the northern part of the plateau (**Figure 71**). The data from this drilling program has not been reported, but Gardner (1957) stated that most samples contained at least 20% SiO_2 and that only two holes intersected bauxite material containing 15-20% SiO_2. Gardner concluded that the deposit consists of mainly tubular laterite at the surface and that most of the pisolitic and nodular bauxite material has been removed by erosion.

BHP Ltd carried out reconnaissance rock chip sampling on the deposit in 1964 as part of a broad search for manganese, bauxite and iron ore deposits in Arnhem Land (BHP 1964b). The best of 14 collected samples assayed 44.84% Al_2O_3, 13.42% SiO_2 and 13.71% Fe. Follow-up exploration work included 89 auger holes (**Figure 71**) that totalled 778 m (Chesnut *et al* 1966). Most of these holes were drilled to 9 m depth. The intersected bauxite horizon averages 1-3 m in thickness (maximum 6 m), but is quite discontinuous. Assayed bauxitic material averaged 35-45% Al_2O_3 and the highest assay was 56.0%. Samples that returned >40% Al_2O_3 were assayed for available Al_2O_3, which varied from 2.9-35.5% (Chesnut *et al* 1968). Of the 14 samples that assayed >50% Al_2O_3, only about 60% of the alumina is present in the form of gibbsite; the remaining 40% is mainly clay. Chesnut *et al* (1966) concluded that the variable quality and discontinuous nature of the bauxitic horizon provided only limited potential for an economic deposit.

Hole ID:	RN 9263				RN 9267				RN 8251
Depth	**0–2 m**	**2–4 m**	**4–6 m**	**6–8 m**	**0–2 m**	**2–4 m**	**4–6 m**	**6–8 m**	**0–2 m**
% Al_2O_3	48.56	50.10	37.89	31.24	50.63	42.33	31.99	32.09	35.97
% SiO_2	7.22	5.53	19.32	23.94	4.85	15.47	28.37	28.81	14.39
% Fe_2O_3	14.42	14.53	21.89	27.51	13.76	17.27	20.16	21.39	28.03
% TiO_2	2.88	2.67	1.90	1.43	2.91	2.27	1.65	1.80	1.93
% CaO	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.00
% Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LOI	26.90	27.20	19.00	15.90	27.80	22.60	17.70	15.80	19.60
TOTAL	99.98	100.02	99.99	100.02	99.96	99.96	99.88	99.91	99.92

Table 20. XRF analyses of bauxite samples obtained from three Dhupuma water bores

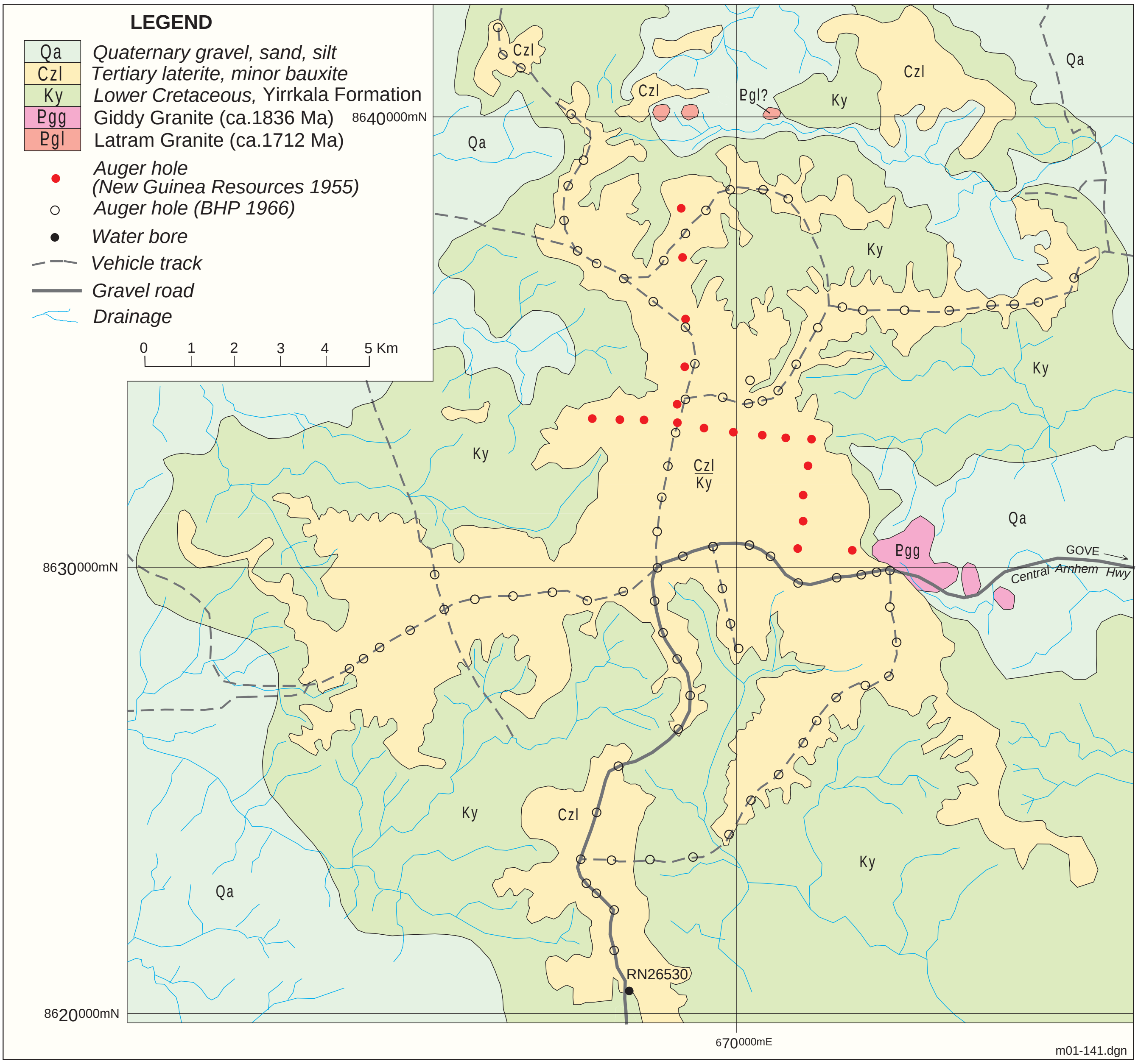


Figure 71. Cato Plateau bauxite prospect (geology modified from Rawlings *et al* 1997)

Umbakumba

Some low-grade, sandy pisolitic and tubular bauxite is partly exposed along cliff sections and in a creek between Umbakumba and Thompsons Bay on Groote Eylandt. This occurrence was briefly investigated by government geologists (Shields 1968, Dodson 1969, Watts 1970), who conducted some geological mapping and geochemical sampling.

Exposures of sandy pisolitic, nodular and tubular bauxite are present along coastal cliffs and incised creeks to the west and south of Umbakumba settlement. Shields (1968) estimated that an area of about 21 km^2 potentially contained bauxite material. The thickness of the bauxite horizon varies from 1-6 m and averages 2-3 m. Ten grab samples were analysed by Shields and these averaged 35.0% Al_2O_3, 30.1% SiO_2 and 26.0% Fe_2O_3. Loose sand was present in some of the assayed samples. The highest assay obtained (UMBA 6) was 41.4% Al_2O_3, 21.6% SiO_2 and 16.0% Fe_2O_3. Watts (1970) sampled five shallow exploratory pits in order to determine the quality of subsurface material. The highest assay from 0.65 m depth in pit 2 returned 41.6% Al_2O_3, 13.9% SiO_2, and 19.4% Fe_2O_3 over 1.2 m.

The potential area of bauxite material is significant, but the low alumina grades and high silica values downgrade the economic viability of the deposit. Pisolitic material identified adjacent to the settlement may be suitable for road aggregate.

Milingimbi

In 1964, United Uranium NL conducted a ground and helicopter regional reconnaissance survey over the coastline between Cobourg Peninsular and Milingimbi, targeting bauxitic laterite, manganese and heavy mineral beach sands (Sturm 1965). No pisolitic laterites were located and only minor tubular laterite was reported at Maningrida. McIntyre Mines Australia Ltd (Bates 1971) conducted an auger drilling program over Cretaceous sediments in the vicinity of Ramingining that resulted in the discovery of the Milingimbi bauxite prospect (AMG 490430mE 8636560mN). This prospect contains a relatively thin (1 m) sandy pisolitic laterite layer. Chip sampling from a 3.2 m deep test pit returned 22.7% Al_2O_3 over 2.4 m and this included 0.9 m grading 32% Al_2O_3 from 1.2 m depth (Bates 1971).

In 1972, CRA Exploration Ltd conducted an auger drilling program over subcropping Raiwalla Shale in the vicinity of the Blyth River (Ehrenbery 1973). Results indicated that any potentially economic laterite zone in that area was probably removed by post-Eocene erosion.

Arafura Basin

Marchinbar Island

Bauxite deposits on Marchinbar Island (**Figure 72**) lie within mining reserve RO 252. These occurrences were first reported by Owen (1949) after he received samples collected by the Northern Territory Coastal Patrol Service that assayed up to 40.8% Av.Al_2O_3. The main lateritic bauxite deposits lie on the east coast of Marchinbar Island and were investigated by the Australian Aluminium Commission in the early 1950s (Owen 1953). Ore resources for the seven tested deposits (**Table 21**) total 9.94 Mt and average 46.0% Av.Al_2O_3 and 4.0% Re.SiO_2 (Owen 1953).

Lateritic bauxite deposits on Marchinbar Island unconformably overlie Neoproterozoic quartz sandstone assigned to the Marchinbar Sandstone (Wessel Group). This sandstone unit is about 240 m thick and dips uniformly to the northwest at about 3° (Plumb and Gostin 1973). In the eastern section ('Body A') of the Sphinx Head deposit (**Figure 74**), bauxite and laterite unconformably overlie siltstone beds assigned to the Neoproterozoic Raiwalla Shale.

The bauxite ore consists predominately of cemented pisoliths of gibbsite, 1-22 mm in diameter, that have light brown and red-brown cores (Owen 1954). A tubular bauxite bed underlies pisolitic ore in several of the deposits that are adjacent to the east coast of the island (eg Able, Sphinx Head, Dog and Easy). Tubular ore reaches a maximum thickness of about 2 m and must lens out to the west, as the westerly deposits are all pisolitic. The underlying laterite is up to 10 m thick and largely consists of nodular ferricrete.

The *Able* deposit is the largest bauxite deposit on the island and occupies an area of about 880 000 m^2 (**Figure 73**). One hundred and forty-two sampling pits were excavated by the Australian Aluminium Commission on a 61x122 m grid. Ore thickness varies from 0.76 m (cut-off) to 5 m and averages 2.4 m (Owen 1953). Pisolitic bauxite forms the bulk of the resource (97%); the remaining 3% (127 000 t) consists of massive and tubular bauxite that underlies the pisolitic ore in the eastern section of the deposit (**Figure 74**). The bauxite horizon is underlain by 3-10 m of laterite, which in turn overlies a 6 m thick quartzite bed ('Grid Quartzite') that was interpreted by Plumb and Gostin (1973) to be the basal arenite unit of the Marchinbar Sandstone.

Bauxite quality usually varies with depth and lower grades are often found in the upper and lower portions of the profile. The upper 0.5-1 m of the bauxite bed in the eastern area of the deposit contains 10-25% quartz sand and fine detrital material. Dry screening of samples from this area gave an average recovery factor of 96%. Silica is in the form of free quartz (1.1%) and reactive (mostly kaolinite) silica (3.0%). Iron oxides (Fe_2O_3), which are mainly in the form of goethite, average 15.7% and TiO_2 averages 3.3%.

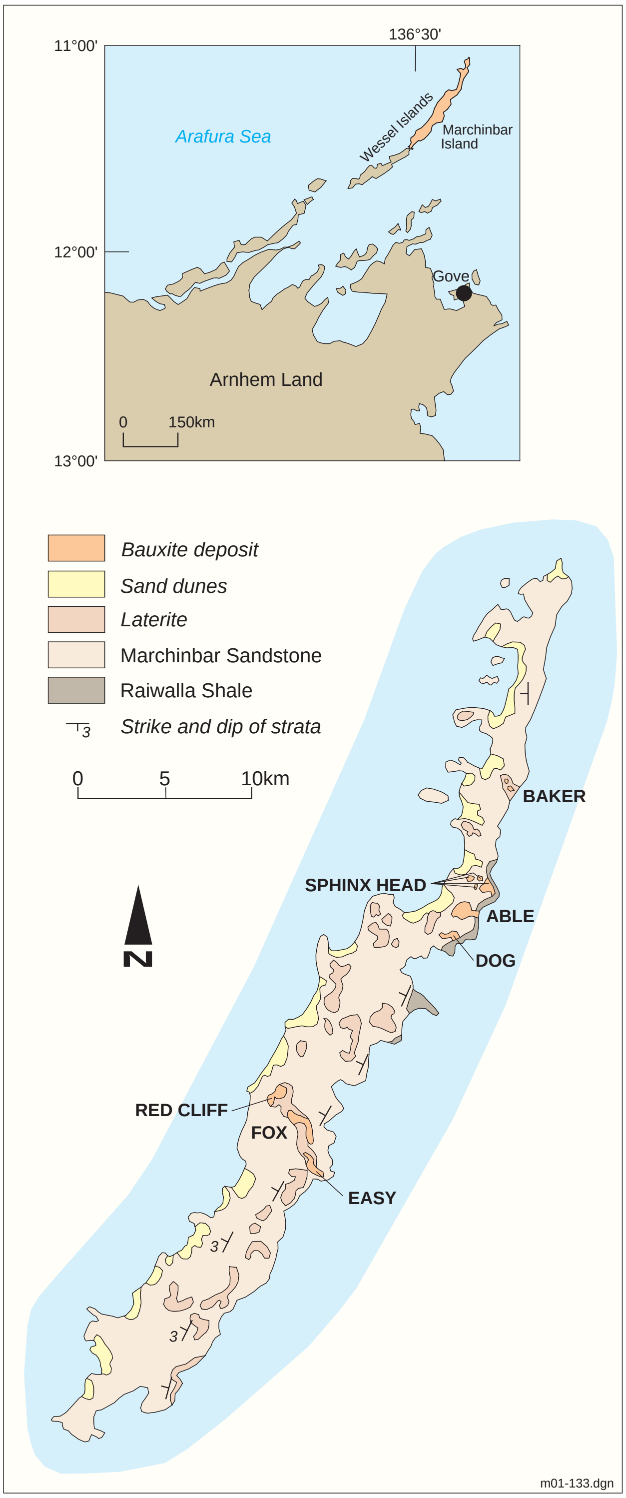


Figure 72. Geology and location of bauxite deposits on Marchinbar Island (modified from Plumb 1965)

Elcho Island

Two bauxite occurrences, separated by about 3 km, were recorded on the eastern side of Elcho Island by Plumb (1965).

Deposit	Tonnage	Av.Al_2O_3 (%)	SiO_2 (%)	Re.SiO_2 (%)	Av thickness (m)
Able	4 700 000	47.1	4.1	3.0	2.4
Dog	1 340 000	47.2	5.1	4.0	2.1
Sphinx Head	1 250 000	43.5	6.5	4.0	1.7
Easy	838 200	45.2	8.3	6.1	1.5
Fox	812 800	42.8	6.8	4.4	1.4
Red Cliff	775 210	43.9	8.8	5.0	1.4
Baker	218 440	47.8	8.6	5.8	1.9

Table 21. Bauxite deposits and resources on Marchinbar Island (source: Owen 1954)

These occurrences consist of loose pisolitic and tubular bauxite horizons that unconformably overlie unaltered Neoproterozoic Marchinbar Sandstone (Plumb and Gostin 1973). The pisolitic layer is about 2 m thick and forms a series of discontinuous exposures over a 3 km strike length. Sand dunes cover the bauxite adjacent to and away from the coast.

A single sample from one of the occurrences assayed 45.7% Al_2O_3 and 25% SiO_2 (Plumb 1965). The high silica value may indicate contamination by quartz grains derived from nearby sand dunes. A laterite sample obtained during reconnaissance work by BHP (1964b) near the southernmost occurrence assayed 25.7% Al_2O_3, 28.0% Tot.SiO_2 and 23.3% Fe_2O_3. This area is essentially untested and may host bauxite deposits comparable to those on Marchinbar Island.

Money Shoal Basin

Lateritic bauxite deposits in the Money Shoal Basin, to the north and northeast of Darwin, include occurrences on the Cobourg Peninsula, Croker Island and Melville Island. Those in the Cobourg Peninsula area and Croker Island (**Figure 75**) have developed over the Cretaceous Bathurst Island Formation whereas those on Melville Island have developed over the Tertiary Van Diemen Sandstone. The bauxitic laterite in the Cobourg Peninsula area is up to 4 m thick and averages about 2 m. It forms a gently north-sloping land surface that is best exposed along the northern coast of the Cobourg Peninsula and Croker Island (Hughes 1978). These deposits lie within Cobourg Peninsula Sanctuary Land Trust and Arnhem Land Aboriginal Land Trust, respectively.

HYL Brown first recorded the occurrence of bauxite on Cobourg Peninsula in 1907. He described a ferruginous pisolitic rock capping Mount Roe (**Figure 75**) that assayed 47.32% Al_2O_3 (Brown 1908). Follow-up work by Owen (1949) established that the thin (0.6-1.4 m thick) pisolitic bauxite layer at Mount Roe overlies a tubular laterite zone that has developed over deeply weathered Cretaceous shale. Rio Tinto Exploration Pty Ltd conducted some reconnaissance work on bauxite deposits on *Croker Island* (Matheson 1957), that were later drill-tested by Reynolds Metals Company (Kidd 1961). Australian Mining and Smelting Company (Patterson 1958) investigated bauxites in the Snake Bay area on Melville Island and United Uranium NL conducted a geochemical sampling survey of bauxite occurrences on the Cobourg Peninsula (Larsen 1965). Swiss Aluminium Mining Australia Pty Ltd conducted geochemical sampling at Cache Point on western Melville Island and prospects on the Cobourg Peninsula (Swiss Aluminium 1969, 1970a, b).

A measured section of a bauxite profile, exposed at Midjari Point on the Cobourg Peninsula, is shown in **Figure 76**. Gibbsite is the principal mineral within the bauxite layers

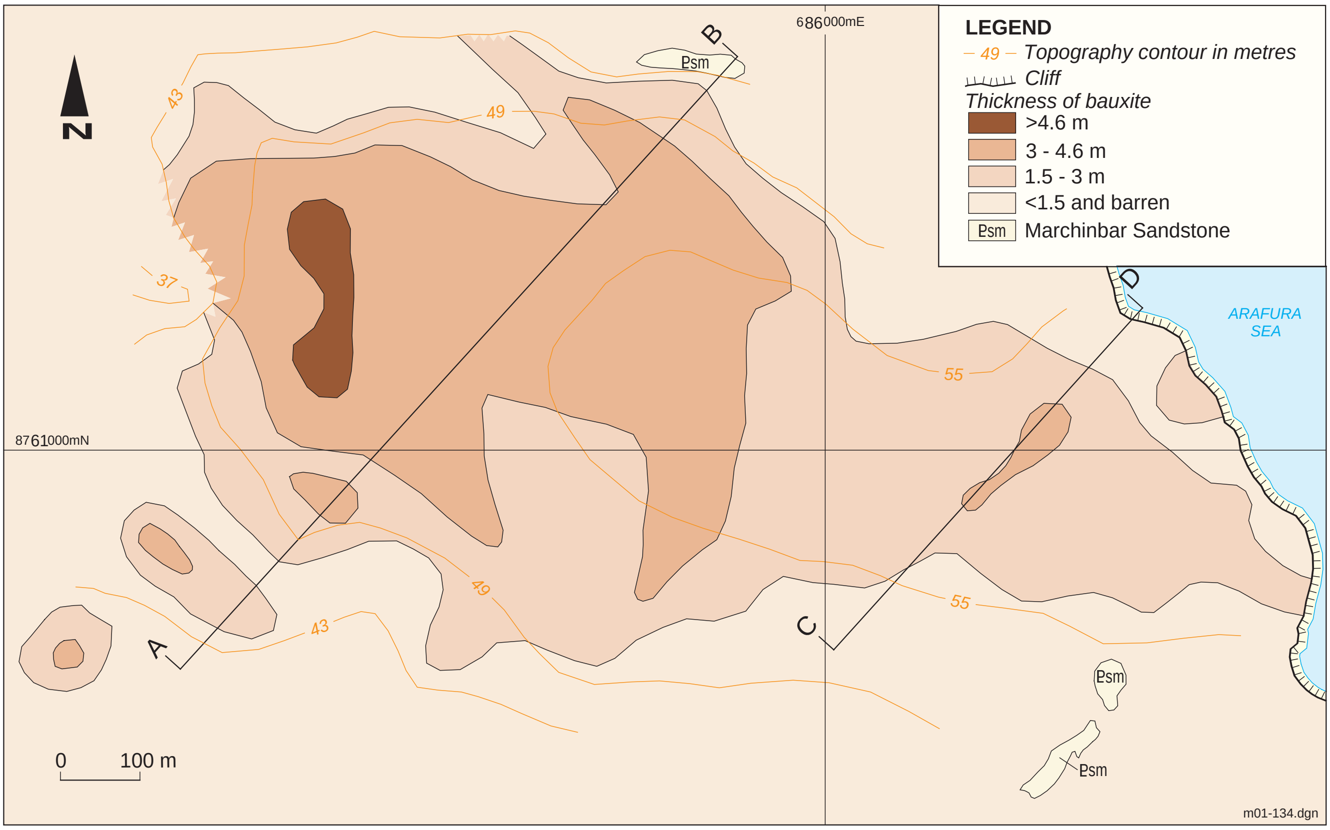


Figure 73. Isopach map of Able bauxite deposit, Marchinbar Island (modified from Owen 1953)

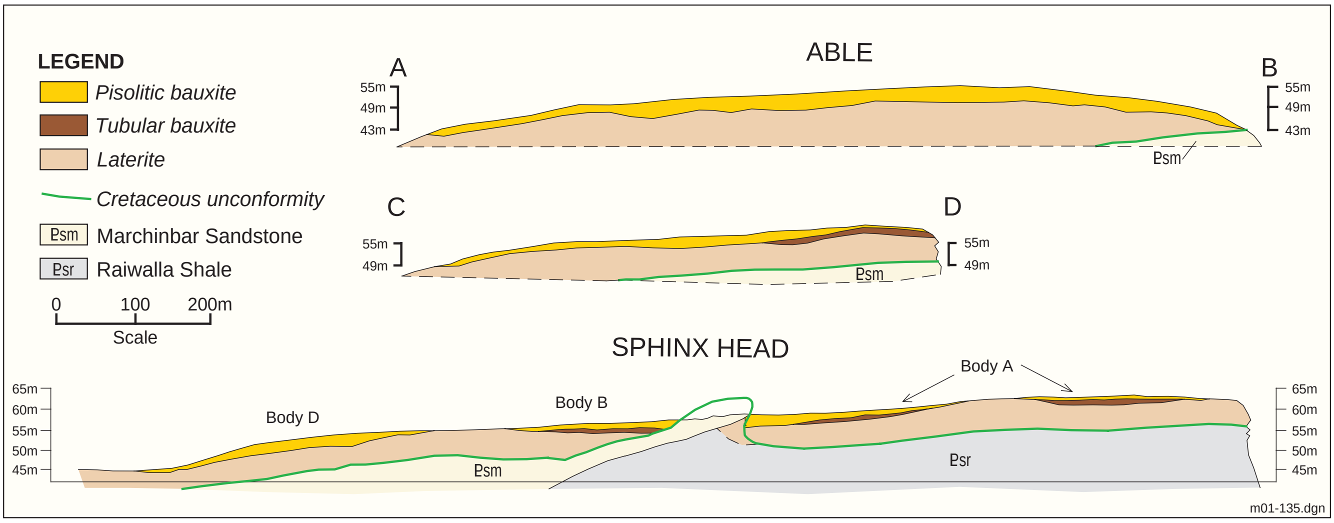


Figure 74. Cross sections of Able and Sphinx Head bauxite deposits (modified from Owen 1953)

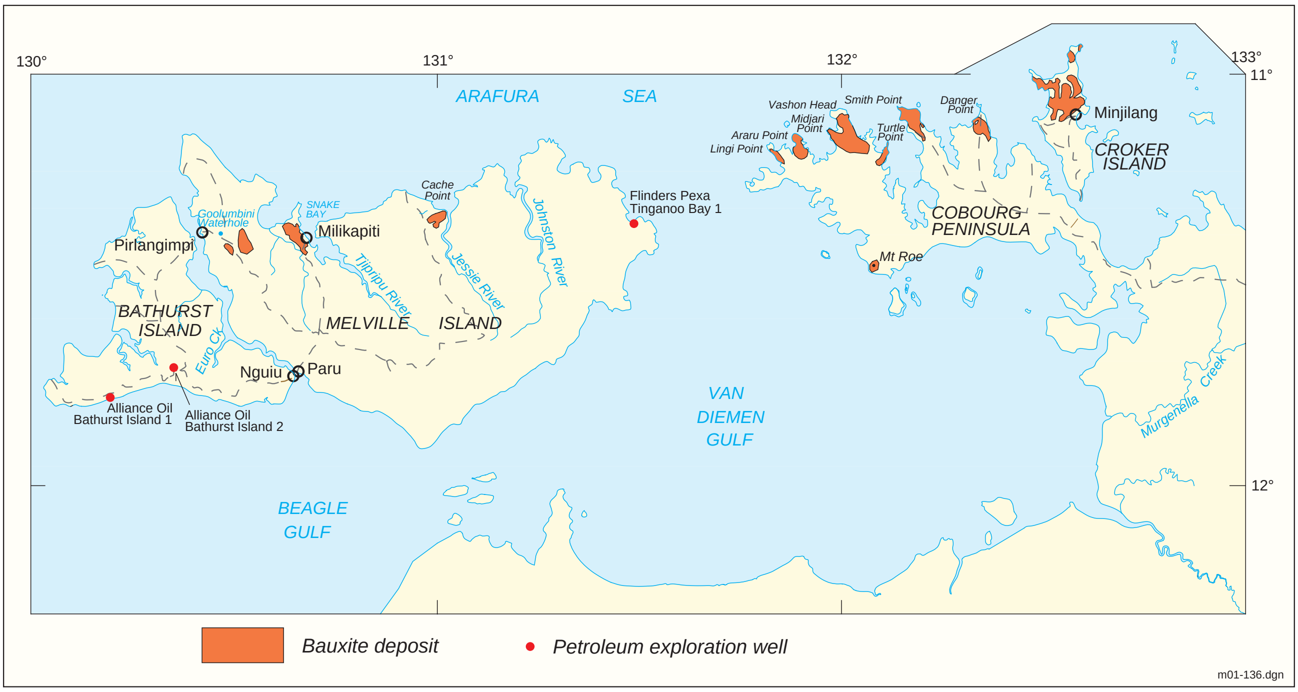


Figure 75. Location of bauxite deposits in Money Shoal Basin

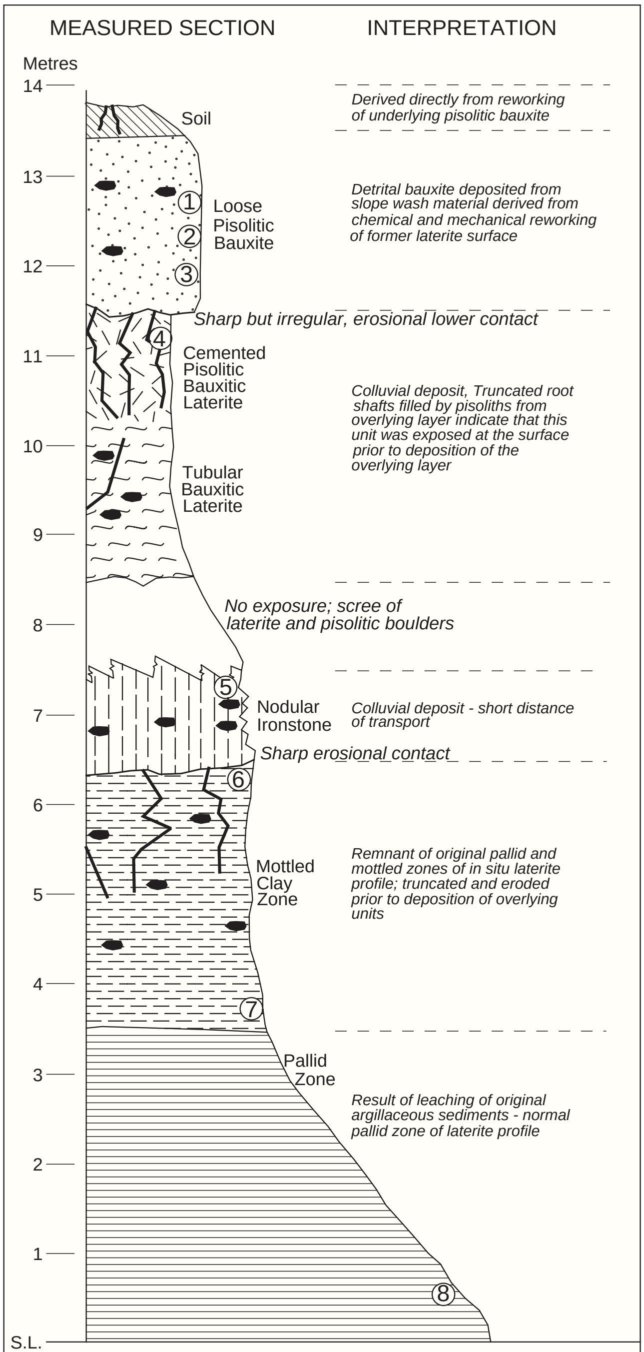
and is commonly in the form of pisoliths that generally vary from 2-8 mm in size. Kaolinite, hematite and minor quartz form the remaining minerals. The pisoliths occur with reworked framework grains of quartz, feldspar, calcite, tourmaline, opaques, broken pisoliths and rock fragments and are set in a matrix composed of very fine quartz and kaolinite (Hughes 1978). Pisolith nuclei consist of older pisoliths, laterite fragments or very fine quartz grains (Hughes 1978). Ferruginous nodules and detrital clasts from underlying beds are commonly scattered through the loose pisolitic layer (**Figure 76**).

A close correlation exists between the distribution of bauxite and thorium anomalies detected by airborne radiometric surveys (Hughes 1978). Thorium concentrations in 13 samples collected from the Cobourg Peninsula ranged from 6-54 ppm and averaged 35 ppm (Hughes 1978). Of the 12 known occurrences of bauxite in the Money Shoal Basin, drilling has been conducted at three deposits to define resources: Vashon Head, Croker Island and Araru Point.

Vashon Head

At Vashon Head on the Cobourg Peninsula, a 1-4.5 m thick bauxite deposit that averages 3 m in the 'good grade' areas occupies an area of about 48 km^2 (**Figures 75**, **77**). The pisolitic bauxite layer overlies a ferruginous nodular laterite that has developed over a shale bed in the Bathurst Island Formation (Weber 1969). Soil overburden averages 0.3 m. Bauxite is thickest in a coastal section in the north and thins to the south where it is replaced by a truncated laterite profile (Hughes 1978).

United Uranium NL conducted surface rock chip sampling and excavated three shallow 2 m deep pits (Larsen 1965). Of



Sample ID	Al_2O_3	SiO_2	Re. SiO_2	Fe_2O_3	TiO_2
①	49.0%	12.8%	12.0%	9.3%	3.3%
②	47.0%	16.0%	13.1%	8.7%	3.2%
③	50.0%	12.7%	11.9%	6.8%	3.7%
④	35.5%	28.5%	26.3%	17.5%	1.8%
⑤	7.9%	25.2%		55.5%	1.6%
⑥	27.5%	32.0%		26.4%	1.2%
⑦	12.5%	70.0%		7.9%	0.8%
⑧	20.4%	42.0%	22.3%	27.0%	1.2%

m01-137.dgn

Figure 76. Bauxite profile at Midjari Point, Cobourg Peninsula (modified from Hughes 1978)

the 37 samples collected, including those from Midjari Point, only five assays returned Al_2O_3 >49% and only two returned Av.Al_2O_3 >40%. Analyses to determine Av.Al_2O_3 and free SiO_2 were conducted on ten samples that averaged 33.9% Av.Al_2O_3, 1.85% free SiO_2 and 13.4% Re.SiO_2.

United Uranium NL followed-up this work with an 81-hole auger drilling program (hole spacing 490 m) over the central portion of the deposit (**Figure 77**). This work outlined inferred resources of 9.7 Mt grading 46.2% Al_2O_3 and 16.1% SiO_2 at an average thickness of 3 m, and 5.8 Mt grading 36.7% Al_2O_3 and 20.2% SiO_2 at an average thickness of 1.7 m. Most of the silica appears to be reactive. Fe_2O_3 content is about 14% and TiO_2 content is about 3% (Weber 1969).

The bauxite resource at Vashon Head appears to be of sub-metallurgical-grade. It has low Av.Al_2O_3 (34%), high reactive silica (>13%) and high iron oxides (14%). However, no ore characterisation work has been conducted and if the clay minerals are loosely bound in the bauxite material, then crushing and washing may reduce the reactive silica content and improve the potential of this deposit as a source of metal-grade bauxite.

Croker Island

On the northern part of Croker Island (**Figure 75**), a bauxite deposit that averages about 1.5 m in thickness and occupies an area of about 80 km^2 has been identified (Kidd 1961). Pisolitic bauxite overlies a hard, red-brown tubular laterite with a sharp contact. Pisoliths are 3-8 mm in diameter. The tubular laterite grades down into a mottled clay zone that in turn overlies grey weathered shale of the Bathurst Island Formation. Soil overburden varies between 0.1-1 m and averages 0.5 m.

Drilling by Reynolds Metals Company included 129 vacuum holes that totalled 519 m. Drillholes were initially at reconnaissance-scale grid spacings of 1500 m and 600 m, but those that intersected bauxite with >30% Av.Al_2O_3 were followed-up with the more closely spaced drilling at 300 m and smaller intervals (Kidd 1961). There are no plans showing the locations of the 300 m grid holes. Based on the drilling program, Reynolds Metals Company estimated an inferred resource of 660 000 t grading 30%+ Av.Al_2O_3 (Kidd 1961). Six grab samples subsequently obtained by United Uranium NL averaged 35.3% Al_2O_3, 31.2% SiO_2, 25.6% Re.SiO_2, 15.4% Fe_2O_3 and 1.85% TiO_2 (Larsen 1965). The location of the Croker Island deposit and its high levels of reactive silica reduce the possibility for commercial exploitation.

Araru Point

A 0.5-2.4 m thick pisolitic bauxite deposit has been outlined over an area of 13 km^2 at Araru Point on the Cobourg Peninsula (**Figure 75**). This deposit was initially sampled by United Uranium NL (Larsen 1965). Four analyses from the deposit averaged 42.7% Al_2O_3 and 31.2% Av.Al_2O_3. Reactive silica for three of the samples averaged 9.1% and iron oxides and TiO_2 averaged 17.2% and 2.4%, respectively.

A follow-up 39-hole auger drilling program at a spacing of 490 m was conducted by United Uranium NL and this work 'indicated' the presence of a resource in the order of 2.4 Mt grading 35-40% Al_2O_3 and 20%+ SiO_2 (Weber 1969). Logs and analyses from this drilling program have not been reported. Additional surface sampling was conducted by Swiss Aluminium Mining Australia Ltd and 12 samples from this work averaged 42.3% Al_2O_3, 18.1% SiO_2, 16.1% Fe_2O_3 and 3.2% TiO_2 (Swiss Aluminium 1970a). Low tonnage and Al_2O_3

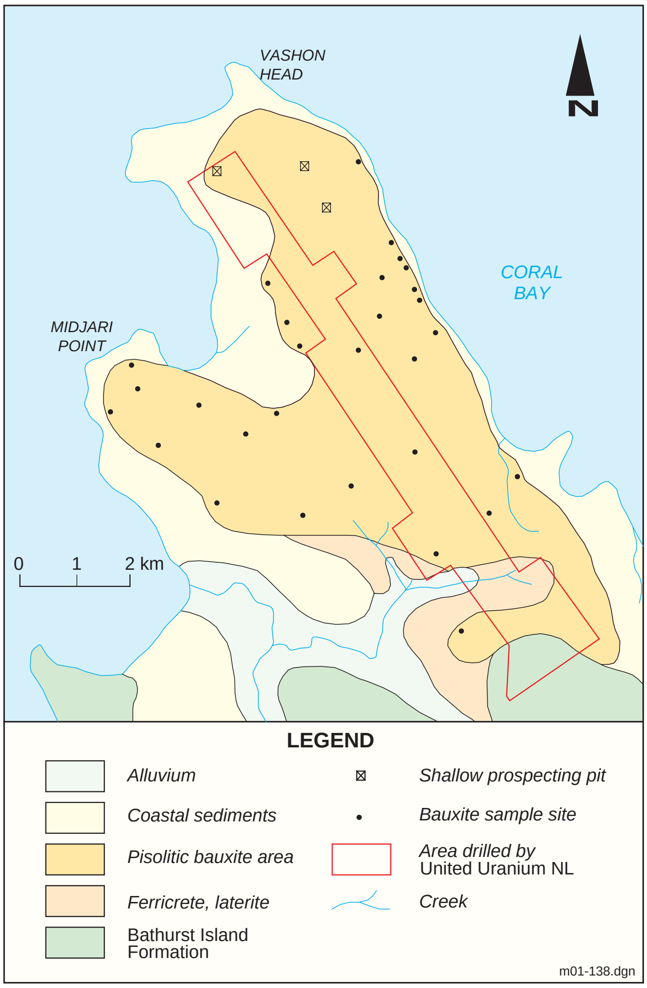


Figure 77. Vashon Head bauxite deposit, Cobourg Peninsula (modified from Weber 1969)

content, as well as high levels of reactive silica reduce the commercial viability of this deposit as a source of metallurgical-grade bauxite.

Ore genesis

The bauxite deposit at Gove is both residual and transported in origin. Bauxite development was enhanced by the presence of all the main factors that promote bauxitisation:

1. *Permeable aluminous parent rocks* - kaolinised arkosic sandstone and shale of the Yirrkala Formation;
2. *Elevated geomorphology* - an extensive, well drained, incised plateau resting on a stable Palaeoproterozoic granitic basement;
3. *Ideal hydrogeologic conditions* - fluctuating, low-standing water table and a high rainfall-monsoonal climate; and
4. *High biological activity* - densely forested tropical flora, dominated by trees with extensive deep root systems.

Most of the large lateritic bauxite deposits in Australia and elsewhere are believed to have originated during the Tertiary (Plumb and Gostin 1973, Bardossy and Aleva 1990). Local constraints on the age of the Gove deposit include an Albian-age (ca 100 Ma) microflora from the underlying Yirrkala Formation and Quaternary (ca 100 000 yrs) carbonate-cemented coastal sand dunes that overlie the bauxite at Rocky Point (Shulmeister and Lees 1992, **Figure 60**). Bauxite formation may thus have started during the Late Cretaceous and continued during favourable climatic periods through the Tertiary. Gentle tilting of the plateau during this period has caused erosion and redistribution of bauxite material.

According to Tilley (1998), bauxite pisoliths at Weipa in Queensland developed by progressive inward hydration of pre-existing drier alumina phases (eg eta-alumina, akdalaite and boehmite) via the precipitation and epigenetic replacement of kaolinite. Bauxite nodules or compound pisoliths formed by deferruginisation and desilicification of ferruginous-kaolinite nodules that originally developed in the mottled zone. A similar multi-stage evolution is probable for pisoliths at Gove based on observations of very similar textures in the bauxite profile.

An unequivocal transported origin for LP ore has been proposed by various authors for the Gove deposit (eg Grubb 1970, Somm 1975, Campbell and Taylor 1994). This layer consists of locally derived sheetwash colluvial material that has been eroded from hillcrests and deposited in lower lying areas (see **Figure 61**).

There is some debate on the origin of cemented pisolitic and tubular ore. Grubb (1970), Plumb and Gostin (1973) and Somm (1975) favoured a transported origin for CP ore, based on the presence of a sharp and undulatory boundary (unconformity?) between CP and Tub ore in many places, and on the widespread occurrence of broken and healed pisoliths and detrital fragments of Tub ore in CP ore.

On the other hand, Campbell and Taylor (1994) favoured a residual origin for CP ore, based on the observation of a gradational boundary between CP and Tub ore in some localities. The sharp irregular contact elsewhere between the CP and Tub horizons may represent an old groundwater interface where there has been an accumulation of leachates (M Emond, Alcan Aluminium Ltd, pers comm 2001). In some geological sections (see Figure 1.2D in Nabalco 1968a), the thickness of CP ore remains constant adjacent to and over topographic highs and this suggests an *in situ* origin.

Grubb (1970) and Plumb and Gostin (1973) favoured a biogenic origin for the tubules in Tub ore at Gove. Nahon (1986) proposed a model by for the formation of laterite pedotubules that involved the reduction and removal of Fe from root channels. Reducing and acidic conditions that would be favourable for such transport are common in the vicinity of these channels. To investigate this model, Stanner (1990) conducted a mineralogical and geochemical examination of tubular (pedotubules) material from the mottled zone at Rocky Bay. Tubules are typically zoned and this zonation consists of a white bleached core zone and wall, encased in a red-brown crust that grades into a pervasive red-brown 'interpipe' region. Stanner concluded that the zonation in the tubules is due to Fe being progressively removed form the 'core' and precipitated in the 'crust' and this is consistent with Nahon's model. The presence of a thin goethite layer between the core and crust suggests that Fe was transported as a reduced Fe^{2+} organic complex (Schwertmann 1985).

Alternatively, Campbell and Taylor (1994) have proposed an inorganic origin for Tub ore that involves a textual and mineralogical reorganisation of the original bauxite by the leaching of iron and formation of kaolinite in the bauxite matrix, followed by the removal of silica. Pisoliths in the highly irregular tubules appear to be too well packed (**Figure 64**) to have been derived from the overlying LP layer. A more plausible explanation for this feature is that the tubules are active solution channels and gibbsitic pisoliths have been converted to kaolinitic pisoliths and vice versa, due to changes in groundwater pH. The tubular bauxite may have developed from the CP layer and may have been chemically eroded in places to produce karstic profiles. In other localities, Tub ore is replaced by loose nodular bauxite (lower nodules). The latter was derived from bauxitisation of the nodular ironstone unit.

At Sphinx Head on Marchinbar Island, bauxite ores that are present over the Marchinbar Sandstone and Raiwalla Shale units have identical profiles (**Figure 74**). Regional laterite development is also extensive within the overlying Elcho Island Formation, but not within the Marchinbar Sandstone (Plumb 1965). Cross-sections through the deposits show that the upper pisolitic bauxite material has had a detrital origin. Lateritised Cretaceous sediments commonly overlie the Raiwalla Shale as this unit was susceptible to pre-Cretaceous erosion and sediments subsequently accumulated in these eroded areas (Plumb and Gostin 1973). The isolated, patchy distribution of bauxite and laterite lenses along the eastern coastline and the westerly pinching out of tubular bauxite may indicate an easterly source.

Marchinbar Island bauxite is very similar in composition and character (reworked pisolitic bauxite) to Gove bauxite. The above observations suggest that the bauxite was probably derived from prolonged intense weathering of Cretaceous sediment remnants that unconformably overlie the Marchinbar Sandstone and Raiwalla Shale.

Bauxite deposits in the Cobourg Peninsula region are very similar in profile and probable genesis to those from the Gove Peninsula. Observations at several deposits and at the measured section at Midjari Point (**Figure 76**) by Hughes (1978) indicate a transported origin for bauxite on the Cobourg Peninsula and Melville Island. A sharp and irregular contact between the pisolitic bauxite layer and underlying tubular bauxite and laterite is interpreted as an erosional boundary. Truncated root shafts are visible immediately below this contact and dispersed ironstone fragments from lower layers are also present. A sharp erosional contact is similarly interpreted below the nodular ironstone unit at Midjari Point (**Figure 76**).

Late Cretaceous or Early Tertiary lateritisation accompanied by erosion and denudation produced the *in situ* laterite profiles preserved on Mount Roe and Mount Bedwell on the Cobourg Peninsula. Gentle tilting to the northwest resulted in mechanical and chemical re-working of the laterite and the deposition of a detrital bauxite horizon that now overlies the truncated laterite in areas along the northern coastline (Hughes 1978). Stranded Pleistocene beach deposits that are composed of consolidated calcarenite, coquina and sandy conglomerate unconformably overlie and abut the bauxitic laterites.

BAUXITE PROSPECTIVITY

Bauxite is widespread across the northern coastline of the Northern Territory. Exploration for this commodity has

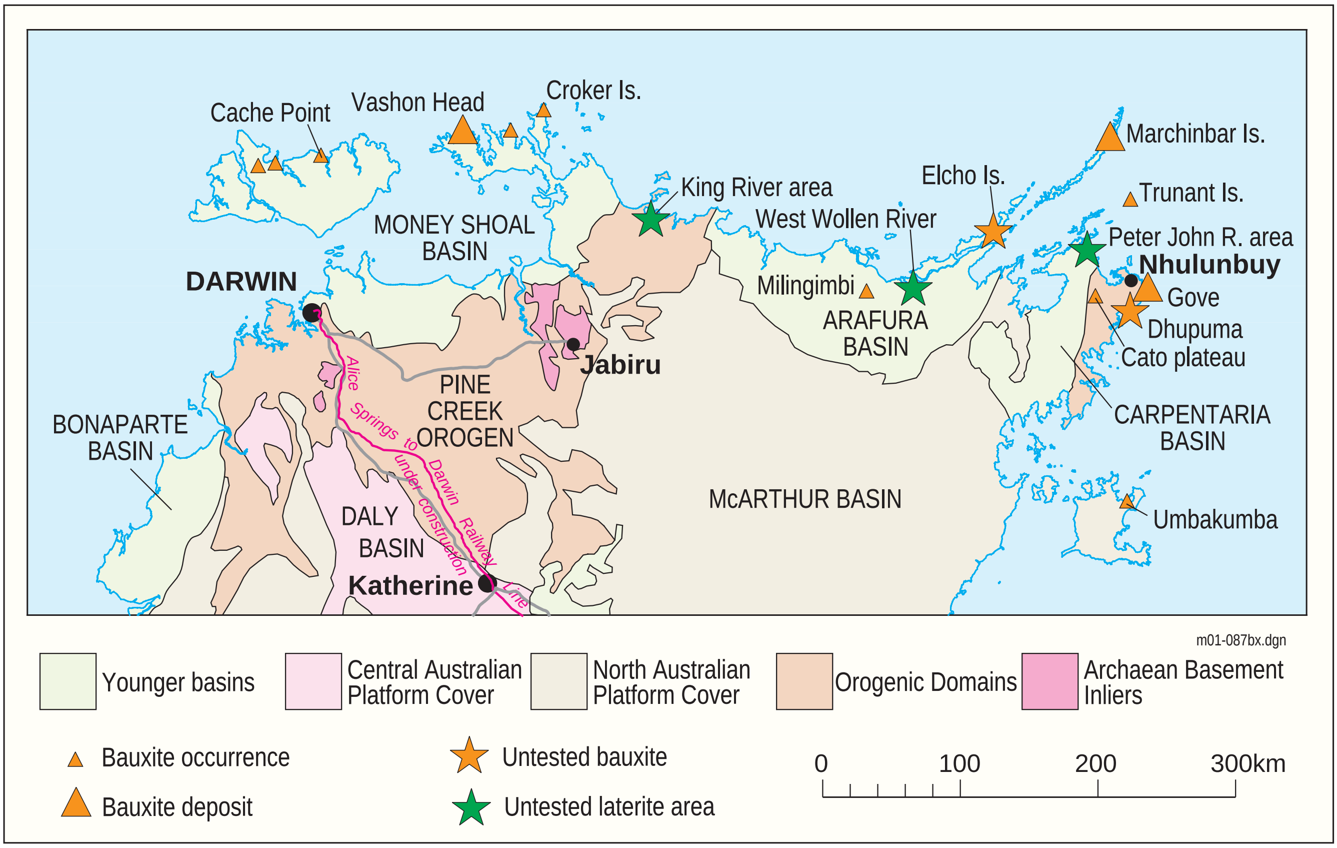


Figure 78. Bauxite prospectivity in the Northern Territory

focussed on this region, but coverage by explorers has been patchy.

Early reconnaissance work has not been followed up at *Dhupuma* and *Elcho Island*. Water bore drill logs and initial geochemical analyses indicate the Dhupuma plateau has >35 Mt of untested lateritic bauxite. Mapping and more sampling using lightweight drilling techniques (eg uncased auger or vacuum) on the Elcho Island occurrences may reveal pockets of bauxite material that are similar in size and composition to those on Marchinbar Island.

Untested favourable lateritic areas include an extensive plateau west of the *Woolen River*, in areas north of the *Peter John River* and elevated areas between *King River* and Jungle Creek (**Figure 78**). BHP Ltd conducted scout auger drilling at 800 m spacing in this area, along a track between Bularriny outstation and Woolen River (Chesnut *et al* 1968). Tertiary laterite (Czl), which contains pisolitic 'earthy' bauxite in places, has developed on the Cretaceous Walker River Formation. Maximum recorded assays include 1 m @ 45.0% Al_2O_3 from 1 m depth (hole WP168) and 1 m @ 30.7% $Av.Al_2O_3$ (hole WP209). In the West Woolen River area, Tertiary laterite with high Th count levels has developed on the Walker River Formation over a 300 km^2 area that lies 60 to 70 m above MSL.

In the King River area (**Figure 78**), Tertiary laterite has developed on undefined Cretaceous sediments that unconformably overlie Palaeoproterozoic rocks assigned to the Nimbuwah Complex. Untested laterite is present over a 140 km^2 area, which is 40-80 m ASL. Laterites, which have elevated Th count levels, have also developed on dissected plateaux, 40-60 m ASL, in areas north of the Peter John River, about 40 km to the west-northwest of Nhulunbuy.

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APPENDIX 1

Summary data on iron occurrences in the Northern Territory. MO = mineral occurrence; MF = Mineral Field; IF = Iron Field; UF = Uranium Field.

IRON ORE									
Name	**Site Id**	**Size**	**Status**	**Model**	**Host Formation**	**Mineral Field**	**MGA E**	**MGA N**	**250K Sheet Name**
ARAFURA BASIN									
Elcho	2335	Small	MO	Surficial enrichment	Elcho Island Formation		561425	8671563	ARNHEM BAY
ARUNTA PROVINCE									
Barney’s	1909	Occurrence	MO	Hydrothermal	Lander Rock beds		268929	7531970	NAPPERBY
Murray Creek	2684	Occurrence	MO	Fe skarn	Lander Rock beds		322629	7606870	MOUNT PEAKE
Patty Well	2209	Occurrence	MO	Hydrothermal	Granite (Pg)		278729	7477970	NAPPERBY
Unnamed	274	Occurrence	MO	Hydrothermal	Granite (Pg)		251529	7480370	NAPPERBY
Unnamed	934	Occurrence	MO	Hydrothermal	Bonya Schist	Jervois MF	599327	7494070	HUCKITTA
Unnamed	970	Occurrence	MO	Hydrothermal	Marshall Granite	Jervois MF	567627	7485170	HUCKITTA
Unnamed	1412	Occurrence	MO	Surficial enrichment	Woodroffe River Beds		301829	7599970	NAPPERBY
Unnamed	1413	Occurrence	MO	Surficial enrichment	Woodroffe River Beds		300729	7511870	NAPPERBY
Unnamed	2071	Occurrence	MO	Hydrothermal	Lander Rock beds		784632	7592965	MOUNT THEO
Harverson Pass	2075	Occurrence	MO	Hydrothermal	Mount Thomas Quartzite		277129	7531670	NAPPERBY
Unnamed	2089	Occurrence	MO	Hydrothermal	Marshall Granite	Jervois MF	579127	7494670	HUCKITTA
Woodforde River	1290	Occurrence	MO	Surficial enrichment	Wickstead Creek beds		304929	7504670	NAPPERBY
GEORGINA BASIN									
Point Spring	2466	Occurrence	MO	Oolitic ironstones	Nora Formation	Jervois MF	586227	7498970	HUCKITTA
Unnamed	925	Occurrence	MO	Surficial enrichment	Elyuah Formation	Jervois MF	587427	7487070	HUCKITTA
McARTHUR BASIN									
Deposit A	2420	Small	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	422627	8374465	URAPUNGA
Deposit B	2421	Small	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	426127	8372665	URAPUNGA
Deposit C	2422	Medium	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	427627	8371665	URAPUNGA
Deposit D	2423	Occurrence	MO	Oolitic ironstones	Sherwin Formation	Roper Iron Field	429627	8366165	URAPUNGA
Deposit E	2424	Occurrence	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	429127	8375165	URAPUNGA
Deposit F	2425	Occurrence	MO	Oolitic ironstones	Sherwin Formation	Roper Iron Field	427127	8361665	URAPUNGA
Deposit G	2426	Small	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	430627	8355165	URAPUNGA
Deposit H	2427	Occurrence	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	430727	8353665	URAPUNGA
Deposit I	2428	Occurrence	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	433727	8357465	URAPUNGA
Deposit J	2429	Occurrence	MO	Oolitic ironstones	Sherwin Formation	Roper Iron Field	434627	8359665	URAPUNGA
Deposit K	2430	Occurrence	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	434327	8356165	URAPUNGA
Deposit L	2431	Occurrence	MO	Oolitic ironstones	Sherwin Formation	Roper Iron Field	433627	8354165	URAPUNGA
Deposit M	2433	Small	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	416227	8357665	URAPUNGA
Deposit N	2432	Occurrence	MO	Oolitic ironstones	Sherwin Formation	Roper Iron Field	409327	8345965	URAPUNGA
Deposit O	2434	Occurrence	MO	Oolitic ironstones	Sherwin Formation	Roper Iron Field	410127	8346965	URAPUNGA
Deposit P	2435	Occurrence	MO	Oolitic ironstones	Sherwin Formation	Roper Iron Field	412327	8354165	URAPUNGA

Appendix 1 (continued)

IRON ORE (continued)									
Name	**Site Id**	**Size**	**Status**	**Model**	**Host Formation**	**Mineral Field**	**MGA E**	**MGA N**	**250K Sheet Name**
McARTHUR BASIN (continued)									
Deposit Q	2411	Occurrence	MO	Surficial enrichment	Bukalorkmi Sandstone	Roper Iron Field	388428	8343865	URAPUNGA
Deposit R	2413	Occurrence	Prospect	Surficial enrichment	Bukalorkmi Sandstone	Roper Iron Field	388128	8341165	HODGSON DOWNS
Deposit S	2412	Occurrence	MO	Surficial enrichment	Bukalorkmi Sandstone	Roper Iron Field	389627	8341865	URAPUNGA
Deposit T	2419	Small	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	391127	8327165	HODGSON DOWNS
Deposit U	2418	Small	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	390127	8325365	HODGSON DOWNS
Deposit V	2417	Small	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	391127	8322165	HODGSON DOWNS
Deposit W	2416	Medium	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	383627	8318865	HODGSON DOWNS
Deposit X	2415	Occurrence	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	378127	8317165	HODGSON DOWNS
Deposit Y	2414	Small	Prospect	Oolitic ironstones	Sherwin Formation	Roper Iron Field	388827	8324065	HODGSON DOWNS
Deposit Z	2436	Occurrence	MO	Oolitic ironstones	Sherwin Formation	Roper Iron Field	383128	8349165	URAPUNGA
Kipper Creek	2663	Small	Prospect	Oolitic ironstones	Mainoru Formation	Roper Iron Field	454027	8380565	URAPUNGA
L3	2680	Occurrence	MO	Surficial enrichment	Balbirini Dolomite	McArthur River MF	547700	8263070	MOUNT YOUNG
Mount Karmain	2437	Occurrence	MO	Oolitic ironstones	Sherwin Formation	Roper Iron Field	357127	8410664	URAPUNGA
Murphy’s	2090	Occurrence	MO	Surficial enrichment	Mount Birch Sandstone	Roper Iron Field	443527	8376165	URAPUNGA
Tawallah Range	2453	Small	MO	Surficial enrichment	Mallapunyah Formation	McArthur River MF	571626	8243066	MOUNT YOUNG
Unnamed	906	Occurrence	MO	Surficial enrichment	Musselbrook Formation		775125	7935169	MOUNT DRUMMOND
Unnamed	1471	Occurrence	Prospect	Surficial enrichment	Kombolgie Formation	Alligator River UF	263526	8537663	MOUNT EVELYN
Unnamed	2095	Occurrence	MO	Surficial enrichment	Mount Reid Beds		440127	8376165	URAPUNGA
Unnamed	2299	Occurrence	MO	Surficial enrichment	Mallapunyah Formation	McArthur River MF	654125	8250866	MOUNT YOUNG
Unnamed	2300	Occurrence	MO	Surficial enrichment	Mallapunyah Formation	McArthur River MF	574425	8228666	BAUHINIA DOWNS
Unnamed	2301	Occurrence	MO	Surficial enrichment	Mallapunyah Formation	McArthur River MF	572625	8229666	BAUHINIA DOWNS
Unnamed	2302	Occurrence	MO	Surficial enrichment	Mallapunyah Formation	McArthur River MF	568426	8229466	BAUHINIA DOWNS
NGALIA BASIN									
Unnamed	258	Occurrence	MO	Sedimentary	Vaughan Springs Quartzite		735432	7523365	MOUNT DOREEN
PINE CREEK OROGEN									
Anomaly A	2685	Occurrence	Prospect	Fe Skarn	Mount Goyder Syenite	Mount Bundey MF	781630	8578260	DARWIN
Anomaly B1	2687	Occurrence	Prospect	Fe Skarn	Mount Goyder Syenite	Mount Bundey MF	782330	8580360	DARWIN
Anomaly G1	2688	Occurrence	Prospect	Fe Skarn	Mount Goyder Syenite	Mount Bundey MF	790630	8578860	DARWIN
B.W.	2271	Occurrence	MO	Hydrothermal	Whites Formation	Rum Jungle MF	712729	8540260	PINE CREEK
Beetson’s	2263	Small	Prospect	Hydrothermal	Whites Formation	Rum Jungle MF	713229	8574060	DARWIN
Beryl	2337	Occurrence	MO	Hydrothermal	Wildman Siltstone	Frances Creek IF	810629	8498460	PINE CREEK
Big Hill	2272	Occurrence	Prospect	Surficial enrichment	Wildman Siltstone	Frances Creek IF	805030	8514960	PINE CREEK
Boots	2325	Occurrence	MO	Surficial enrichment	Koolpin Formation	Frances Creek IF	800829	8518360	PINE CREEK
Bowerbird	2273	Occurrence	MO	Surficial enrichment	Wildman Siltstone	Frances Creek IF	804529	8514560	PINE CREEK
Bromil	2270	Occurrence	MO	Surficial enrichment	Koolpin Formation	Rum Jungle MF	728629	8580661	DARWIN
Craig Creek	2279	Occurrence	MO	Surficial enrichment	Koolpin Formation	Cullen MF	814128	8542860	PINE CREEK

Appendix 1 (continued)

IRON ORE (continued)									
Name	**Site Id**	**Size**	**Status**	**Model**	**Host Formation**	**Mineral Field**	**MGA E**	**MGA N**	**250K Sheet Name**
PINE CREEK OROGEN (continued)									
Crusader 1	2469	Occurrence	MO	Surficial enrichment	Mundogie Sandstone		207226	8617463	ALLIGATOR RIVER
Daly River Road	2261	Small	Prospect	Surficial enrichment	Petrel Formation	Cullen MF	729729	8510561	PINE CREEK
Darwin River	567	Occurrence	MO	Hydrothermal	Wildman Siltstone	Rum Jungle MF	713129	8582161	DARWIN
Egg Cup	2326	Occurrence	MO	Surficial enrichment	Koolpin Formation	Frances Creek IF	802080	8514460	PINE CREEK
Elizabeth Marion	2336	Occurrence	Prospect	Surficial enrichment	Wildman Siltstone	Frances Creek IF	807829	8498461	PINE CREEK
Frances Creek East	2274	Small	Prospect	Hydrothermal	Masson Formation	Frances Creek IF	821329	8497960	PINE CREEK
Hayes Creek South	2651	Occurrence	MO	Surficial enrichment	Stray Creek Sandstone	Cullen MF	770129	8490461	PINE CREEK
Helene 1	2275	Occurrence	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	808629	8496761	PINE CREEK
Helene 10	2340	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	808129	8493411	PINE CREEK
Helene 11	2629	Small	MO	Hydrothermal	Wildman Siltstone	Frances Creek IF	808429	8495061	PINE CREEK
Helene 2	2276	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	808829	8495961	PINE CREEK
Helene 3	2290	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	808829	8495661	PINE CREEK
Helene 4	2291	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	808929	8494961	PINE CREEK
Helene 5	2293	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	808929	8494861	PINE CREEK
Helene 6/7	2294	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	808929	8494261	PINE CREEK
Helene 9	2292	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	808129	8494261	PINE CREEK
Howley	2277	Occurrence	Prospect	Hydrothermal	Koolpin Formation	Cullen MF	758629	8501561	PINE CREEK
J.C. & K.C.	2269	Occurrence	MO	Surficial enrichment	Koolpin Formation	Rum Jungle MF	715629	8584261	DARWIN
Jasmine Centre	2284	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	811229	8497461	PINE CREEK
Jasmine East	2632	Occurrence	Prospect	Hydrothermal	Wildman Siltstone	Frances Creek IF	811629	8497161	PINE CREEK
Jasmine West	2338	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	810729	8497661	PINE CREEK
Kapalga	2259	Occurrence	MO	Surficial enrichment	Mundogie Sandstone		207126	8612163	ALLIGATOR RIVER
L.C.	2268	Occurrence	MO	Surficial enrichment	Koolpin Formation	Rum Jungle MF	719529	8583561	DARWIN
Lewis	2327	Occurrence	MO	Surficial enrichment	Koolpin Formation	Cullen MF	801429	8515160	PINE CREEK
Marrakai	2280	Occurrence	MO	Surficial enrichment	Koolpin Formation		741628	8577761	DARWIN
Miller’s	2322	Small	Prospect	Surficial enrichment	Wildman Siltstone	Frances Creek IF	804629	8512360	PINE CREEK
Mount Bundey	2403	Small	Abandoned mine	Fe skarn	Wildman Siltstone	Mount Bundey MF	781628	8578161	DARWIN
Mount Shoobridge	2461	Small	Prospect	Surficial enrichment	Petrel Formation	Cullen MF	742629	8500461	PINE CREEK
Ochre Hill	2285	Small	Prospect	Hydrothermal	Wildman Siltstone	Frances Creek IF	809129	8502360	PINE CREEK
Porcupine	2323	Occurrence	MO	Surficial enrichment	Wildman Siltstone	Frances Creek IF	804880	8515460	PINE CREEK
Rosemary	2339	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	810629	8497161	PINE CREEK
Rosemary Extended	2672	Occurrence	Prospect	Hydrothermal	Wildman Siltstone	Frances Creek IF	810430	8497860	PINE CREEK
Rum Jungle Iron Ore	2262	Small	Prospect	Hydrothermal	Whites Formation	Rum Jungle MF	715629	8563561	DARWIN
Saddle 1	2286	Small	Prospect	Hydrothermal	Wildman Siltstone	Frances Creek IF	808329	8503560	PINE CREEK
Saddle 2	2682	Occurrence	Prospect	Hydrothermal	Wildman Siltstone	Frances Creek IF	807530	8504660	PINE CREEK
Saddle East	2631	Small	Prospect	Hydrothermal	Wildman Siltstone	Frances Creek IF	808330	8504360	PINE CREEK
Saddle Extended	2287	Small	Prospect	Hydrothermal	Wildman Siltstone	Frances Creek IF	806629	8506560	PINE CREEK

Appendix 1 (continued)

IRON ORE (continued)									
Name	**Site Id**	**Size**	**Status**	**Model**	**Host Formation**	**Mineral Field**	**MGA E**	**MGA N**	**250K Sheet Name**
PINE CREEK OROGEN (continued)									
Saddle West	2633	Occurrence	MO	Hydrothermal	Wildman Siltstone	Frances Creek IF	806729	8505460	PINE CREEK
Thelma 1	2289	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	809429	8497661	PINE CREEK
Thelma 2	2288	Small	Abandoned mine	Hydrothermal	Wildman Siltstone	Frances Creek IF	809829	8497261	PINE CREEK
Thelma 3	2324	Occurrence	Prospect	Hydrothermal	Wildman Siltstone	Frances Creek IF	810077	8496860	PINE CREEK
Thelma Rosemary	2630	Small	Prospect	Hydrothermal	Wildman Siltstone	Frances Creek IF	810529	8496661	PINE CREEK
Unnamed	443	Occurrence	MO	Surficial enrichment	Tollis Formation	Cullen MF	186828	8428264	KATHERINE
Unnamed	2282	Occurrence	MO	Surficial enrichment	Depot Creek Sandstone		686929	8536961	PINE CREEK
Yarram	2691	Small	Prospect	Surficial enrichment	Coomalie Dolomite	Rum Jungle MF	714830	8563660	DARWIN
SOUTH NICHOLSON BASIN									
Unnamed	2465	Occurrence	MO	Oolitic ironstones	Mullera Formation		765125	7948169	MOUNT DRUMMOND
TENNANT INLIER									
Warrego	2575	Small	Abandoned mine	Hydrothermal	Warramunga Formation	Tennant Creek MF	377128	7849268	TENNANT CREEK
Nobles Nob	1606	Small	Abandoned mine	Hydrothermal	Warramunga Formation	Tennant Creek MF	425727	7820069	TENNANT CREEK
Peko	2572	Small	Abandoned mine	Hydrothermal	Warramunga Formation	Tennant Creek MF	424927	7823969	TENNANT CREEK

APPENDIX 2

Summary data on manganese occurrences in the Northern Territory. MO = mineral occurrence; Fm = Formation.

MANGANESE

Name	Site Id	Size	Status	Model	Host Formation	MGA E	MGA N	250K Sheet Name	Comments
AMADEUS BASIN									
Fenn Gap	700	Occurrence	MO	Surficial enrichment	Bitter Springs Formation	361929	7368471	ALICE SPRINGS	
Wangatinya	1476	Occurrence	MO	Hydrothermal	Pacoota Sandstone	715133	7380165	MOUNT LIEBIG	9 samples averaged 44% Mn
Unnamed	2278	Occurrence	MO	Surficial enrichment	Winnall Beds	690433	7212066	AYERS ROCK	
ARUNTA PROVINCE									
Unnamed	2074	Occurrence	MO	Surficial enrichment	Pine Hill Formation	266629	7541970	NAPPERBY	
Unnamed	2212	Occurrence	MO	Surficial enrichment	Central Mount Stewart Fm	320429	7578970	MOUNT PEAKE	
CARPENTARIA BASIN									
Batten Creek	2657	Occurrence	Prospect	Sedimentary	Walker River Formation	622525	8238366	MOUNT YOUNG	BCP10: 6 m @ 15% Mn
Brumby	2669	Occurrence	Prospect	Sedimentary	Walker River Formation	538000	8328350	MOUNT YOUNG	TR067: 2 m @ 18% Mn
Caledon 1	474	Occurrence	MO	Sedimentary	Yirrkala Formation	651526	8595364	ARNHEM BAY	Sandy Mn lenses
Caledon 2	2655	Occurrence	MO	Sedimentary	Yirrkala Formation	654626	8594664	ARNHEM BAY	Untested 2 m thick pisolitic Mn
Deposit A	2440	Large	Operating mine	Sedimentary	Walker River Formation	656126	8452665	BLUE MUD BAY	Groote Eylandt deposits with Past Production of 50 Mt @ 49% Mn. Total Resource of 212 Mt @ 47.5% Mn
Deposit D	2438	Large	Operating mine	Sedimentary	Walker River Formation	656626	8445665	ROPER RIVER	
Deposit F	2441	Large	Operating mine	Sedimentary	Walker River Formation	657626	8454665	BLUE MUD BAY	
Deposit H	2675	Occurrence	Prospect	Sedimentary	Walker River Formation	658200	8443100	ROPER RIVER	
Deposit J	2439	Small	Prospect	Sedimentary	Walker River Formation	655900	8441300	ROPER RIVER	
Deposit K	2676	Occurrence	Prospect	Sedimentary	Walker River Formation	662300	8435800	CAPE BEATRICE	
L4	2678	Occurrence	MO	Sedimentary	Walker River Formation	544300	8290470	MOUNT YOUNG	
Peter John	776	Occurrence	Prospect	Surficial enrichment	Yirrkala Formation	663125	8644264	ARNHEM BAY	
Probable Island	2653	Occurrence	MO	Sedimentary	Walker River Formation	612725	8662463	ARNHEM BAY	Two untested Mn lenses
South Rosie Creek	2454	Small	Prospect	Sedimentary	Walker River Formation	583026	8269566	MOUNT YOUNG	4.5-5.5 Mt @ 25% Mn resource
Yiyintyi	2671	Occurrence	MO	Sedimentary	Walker River Formation	584000	8277300	MOUNT YOUNG	YER6: 2 m @ 39.1% Mn
EROMANGA BASIN									
Umbeara	2677	Occurrence	MO	Surficial enrichment	Hooray Sandstone	388288	7139472	FINKE	
McARTHUR BASIN									
Camp No 1	2174	Occurrence	MO	Surficial enrichment	Karns Dolomite	759125	8093167	CALVERT HILLS	
Jacks Spring Lick	2136	Occurrence	MO	Surficial enrichment	Karns Dolomite	740125	8102167	CALVERT HILLS	
L9	2679	Occurrence	MO	Surficial enrichment	Mainoru Formation	555700	8236770	MOUNT YOUNG	
Manganese 2	2153	Occurrence	MO	Surficial enrichment	Karns Dolomite	756625	8096667	CALVERT HILLS	
Manganese 3	2147	Occurrence	Prospect	Surficial enrichment	Karns Dolomite	758625	8097667	CALVERT HILLS	
Masterton 2	2163	Small	Prospect	Surficial enrichment	Karns Dolomite	760125	8097667	CALVERT HILLS	40-50 000 t @ 32% Mn resource
No. 3	2185	Occurrence	MO	Surficial enrichment	Karns Dolomite	759126	8088167	CALVERT HILLS	
No. 5	2127	Occurrence	MO	Surficial enrichment	Karns Dolomite	740125	8116167	CALVERT HILLS	

Appendix 2 (continued)

MANGANESE (continued)

Name	Site Id	Size	Status	Model	Host Formation	MGA E	MGA N	250K Sheet Name	Comments
McARTHUR BASIN (continued)									
Photo	2116	Occurrence	MO	Surficial enrichment	Karns Dolomite	753125	8118167	CALVERT HILLS	
Point Blane	814	Occurrence	MO	Surficial enrichment	Undefined	627526	8531564	BLUE MUD BAY	
Robinson River 1	1959	Occurrence	MO	Surficial enrichment	Karns Dolomite	723325	8199966	ROBINSON RIVER	
Robinson River 2	1960	Occurrence	MO	Surficial enrichment	Karns Dolomite	723625	8200666	ROBINSON RIVER	
Round Hill Island	2654	Occurrence	MO	Surficial enrichment	Undefined	618526	8529064	BLUE MUD BAY	
Unnamed	449	Occurrence	MO	Surficial enrichment	Undefined	661126	8583164	ARNHEM BAY	
Unnamed	451	Occurrence	MO	Surficial enrichment	Undefined	655926	8587164	ARNHEM BAY	
Unnamed	456	Occurrence	MO	Surficial enrichment	Undefined	648526	8587464	ARNHEM BAY	
Unnamed	459	Occurrence	MO	Surficial enrichment	Undefined	646726	8592064	ARNHEM BAY	
Unnamed	462	Occurrence	MO	Surficial enrichment	Undefined	646826	8593664	ARNHEM BAY	
Unnamed	465	Occurrence	MO	Surficial enrichment	Undefined	645526	8595264	ARNHEM BAY	
Unnamed	468	Occurrence	MO	Surficial enrichment	Undefined	650026	8592664	ARNHEM BAY	
Unnamed	471	Occurrence	MO	Surficial enrichment	Undefined	650626	8593964	ARNHEM BAY	
Unnamed	478	Occurrence	MO	Surficial enrichment	Undefined	656226	8602464	ARNHEM BAY	
Unnamed	482	Occurrence	MO	Surficial enrichment	Undefined	658326	8603664	ARNHEM BAY	
Unnamed	485	Occurrence	MO	Surficial enrichment	Undefined	662226	8604364	ARNHEM BAY	
Unnamed	489	Occurrence	MO	Surficial enrichment	Undefined	662526	8633664	ARNHEM BAY	
Unnamed	492	Occurrence	MO	Surficial enrichment	Undefined	662026	8642464	ARNHEM BAY	
Unnamed	495	Occurrence	MO	Surficial enrichment	Undefined	660725	8643664	ARNHEM BAY	
Unnamed	498	Occurrence	MO	Surficial enrichment	Undefined	581626	8564963	ARNHEM BAY	
Unnamed	502	Occurrence	MO	Surficial enrichment	Undefined	600526	8615063	ARNHEM BAY	
Unnamed	505	Occurrence	MO	Surficial enrichment	Undefined	587126	8613163	ARNHEM BAY	
Unnamed	507	Occurrence	MO	Surficial enrichment	Undefined	592226	8612063	ARNHEM BAY	
Unnamed	510	Occurrence	MO	Surficial enrichment	Undefined	595326	8621463	ARNHEM BAY	
Unnamed	514	Occurrence	MO	Surficial enrichment	Undefined	591026	8619463	ARNHEM BAY	
Unnamed	517	Occurrence	MO	Surficial enrichment	Undefined	597126	8619863	ARNHEM BAY	
Unnamed	521	Occurrence	MO	Surficial enrichment	Undefined	600826	8632663	ARNHEM BAY	
Unnamed	523	Occurrence	MO	Surficial enrichment	Undefined	601626	8635363	ARNHEM BAY	
Unnamed	526	Occurrence	MO	Surficial enrichment	Undefined	605525	8639663	ARNHEM BAY	
Unnamed	802	Occurrence	MO	Surficial enrichment	Undefined	632626	8470664	BLUE MUD BAY	
Unnamed	803	Occurrence	MO	Surficial enrichment	Undefined	630126	8486164	BLUE MUD BAY	
Unnamed	804	Occurrence	MO	Surficial enrichment	Undefined	669826	8555864	PORT LANGDON	
Unnamed	805	Occurrence	MO	Surficial enrichment	Undefined	648326	8530164	BLUE MUD BAY	
Unnamed	806	Occurrence	MO	Surficial enrichment	Undefined	636126	8559164	BLUE MUD BAY	
Unnamed	807	Occurrence	MO	Surficial enrichment	Undefined	658626	8551164	BLUE MUD BAY	
Unnamed	809	Occurrence	MO	Surficial enrichment	Undefined	655826	8556464	BLUE MUD BAY	
Unnamed	812	Occurrence	MO	Surficial enrichment	Undefined	652826	8557964	BLUE MUD BAY	

Appendix 2 (continued)

MANGANESE (continued)

Name	Site Id	Size	Status	Model	Host Formation	MGA E	MGA N	250K Sheet Name	Comments
McARTHUR BASIN (continued)									
Unnamed	813	Occurrence	MO	Surficial enrichment	Undefined	654926	8559464	BLUE MUD BAY	
Unnamed	815	Occurrence	MO	Surficial enrichment	Undefined	627726	8538164	BLUE MUD BAY	
Unnamed	816	Occurrence	MO	Surficial enrichment	Undefined	634126	8547164	BLUE MUD BAY	
Unnamed	817	Occurrence	MO	Surficial enrichment	Undefined	613526	8542664	BLUE MUD BAY	
Unnamed	818	Occurrence	MO	Surficial enrichment	Undefined	585126	8543664	BLUE MUD BAY	
Unnamed	819	Occurrence	MO	Surficial enrichment	Undefined	584626	8551164	BLUE MUD BAY	
Unnamed	820	Occurrence	MO	Surficial enrichment	Undefined	579126	8549663	BLUE MUD BAY	
Unnamed	821	Occurrence	MO	Surficial enrichment	Undefined	576626	8544664	BLUE MUD BAY	
Unnamed	823	Occurrence	MO	Surficial enrichment	Undefined	572026	8508364	BLUE MUD BAY	
Unnamed	824	Occurrence	MO	Surficial enrichment	Undefined	565126	8524164	BLUE MUD BAY	
Unnamed	825	Occurrence	MO	Surficial enrichment	Undefined	572626	8526164	BLUE MUD BAY	
Unnamed	826	Occurrence	MO	Surficial enrichment	Undefined	563626	8510964	BLUE MUD BAY	
Unnamed	827	Occurrence	MO	Surficial enrichment	Undefined	555426	8464464	BLUE MUD BAY	
Unnamed	828	Occurrence	MO	Surficial enrichment	Undefined	567126	8486564	BLUE MUD BAY	
Unnamed	829	Occurrence	MO	Surficial enrichment	Undefined	537926	8465964	BLUE MUD BAY	
Unnamed	830	Occurrence	MO	Surficial enrichment	Undefined	677426	8567464	GOVE	
Unnamed	831	Occurrence	MO	Surficial enrichment	Undefined	668626	8575864	GOVE	
Unnamed	832	Occurrence	MO	Surficial enrichment	Undefined	663126	8587164	GOVE	
Unnamed	833	Occurrence	MO	Surficial enrichment	Undefined	672626	8616864	GOVE	
Unnamed	834	Occurrence	MO	Surficial enrichment	Undefined	675526	8614864	GOVE	
Unnamed	835	Occurrence	MO	Surficial enrichment	Undefined	674126	8609664	GOVE	
Unnamed	836	Occurrence	MO	Surficial enrichment	Undefined	674626	8608064	GOVE	
Unnamed	837	Occurrence	MO	Surficial enrichment	Undefined	678026	8612264	GOVE	
Unnamed	838	Occurrence	MO	Surficial enrichment	Undefined	667626	8617964	GOVE	
Unnamed	839	Occurrence	MO	Surficial enrichment	Undefined	667826	8621164	GOVE	
Unnamed	840	Occurrence	MO	Surficial enrichment	Undefined	673126	8620364	GOVE	
Unnamed	842	Occurrence	MO	Surficial enrichment	Undefined	667826	8628564	GOVE	
Unnamed	843	Occurrence	MO	Surficial enrichment	Undefined	673026	8632464	GOVE	
Unnamed	844	Occurrence	MO	Surficial enrichment	Undefined	664726	8641164	GOVE	
Unnamed	845	Occurrence	MO	Surficial enrichment	Undefined	665125	8648464	GOVE	
Unnamed	846	Occurrence	MO	Surficial enrichment	Undefined	668625	8648464	GOVE	
Unnamed	847	Occurrence	MO	Surficial enrichment	Undefined	656026	8577264	ARNHEM BAY	
Unnamed	848	Occurrence	MO	Surficial enrichment	Undefined	670125	8659164	GOVE	
Unnamed	849	Occurrence	MO	Surficial enrichment	Undefined	670625	8660664	GOVE	
Unnamed	850	Occurrence	MO	Surficial enrichment	Undefined	656126	8575164	ARNHEM BAY	
Unnamed	851	Occurrence	MO	Surficial enrichment	Undefined	654026	8578764	ARNHEM BAY	
Unnamed	1122	Occurrence	MO	Surficial enrichment	Undefined	666726	8612864	GOVE	

Appendix 2 (continued)

MANGANESE (continued)

Name	Site Id	Size	Status	Model	Host Formation	MGA E	MGA N	250K Sheet Name	Comments
McARTHUR BASIN (continued)									
Unnamed	1951	Occurrence	MO	Surficial enrichment	Balbirini Dolomite	588225	8194466	BAUHINIA DOWNS	
Unnamed	2442	Occurrence	MO	Surficial enrichment	Undefined	675126	8610164	GOVE	
Unnamed	2444	Occurrence	MO	Surficial enrichment	Undefined	670626	8561064	ARNHEM BAY	
PINE CREEK OROGEN									
El Dollarado	1418	Occurrence	Abandoned mine	Surficial enrichment	Mount Bonnie Formation	192728	8489064	MOUNT EVELYN	
Green Ant Creek	569	Occurrence	MO	Surficial enrichment	Petrel Formation	739729	8502361	PINE CREEK	
McLean’s	2462	Occurrence	Abandoned mine	Surficial enrichment	Petrel Formation	744429	8501261	PINE CREEK	Past production: 540 t @ 38% Mn
TENNANT INLIER									
Bootu 1	2082	Small	Abandoned mine	Hydrothermal	Bootu Formation	407828	7932168	HELEN SPRINGS	Mn lenses up to 12 m thick over a 13 km conductive GEOTEM zone with potential for >20 Mt. Low silica, high-grade Mn ore in lower 2 m
Bootu 2	2083	Small	Prospect	Hydrothermal	Bootu Formation	406928	7932268	HELEN SPRINGS	
Bootu 3	2084	Small	Abandoned mine	Hydrothermal	Bootu Formation	407028	7932668	HELEN SPRINGS	
Bootu 4	2644	Small	Prospect	Hydrothermal	Bootu Formation	407228	7935018	HELEN SPRINGS	
Burke Creek	2649	Occurrence	MO	Surficial enrichment	Mullaman Beds	364928	7967868	HELEN SPRINGS	
Mucketty	2081	Small	Abandoned mine	Hydrothermal	Bootu Formation	401378	7936168	HELEN SPRINGS	Past production: 13 300 t @ 42% Mn
Mucketty 2	2650	Occurrence	Abandoned mine	Hydrothermal	Bootu Formation	401328	7935368	HELEN SPRINGS	
Renner Springs No1	2492	Small	Abandoned mine	Hydrothermal	Shillinglaw Formation	357328	7975368	HELEN SPRINGS	
Renner Springs No2	2645	Occurrence	MO	Hydrothermal	Shillinglaw Formation	356028	7976668	HELEN SPRINGS	
Renner Springs No3	2646	Occurrence	MO	Hydrothermal	Shillinglaw Formation	358128	7973868	HELEN SPRINGS	
Renner Springs No4	2647	Occurrence	MO	Hydrothermal	Shillinglaw Formation	357828	7971968	HELEN SPRINGS	
Renner Springs No5	2648	Occurrence	MO	Surficial enrichment	Mullaman Beds	361828	7971968	HELEN SPRINGS	
Unnamed	2402	Occurrence	MO	Hydrothermal	Bootu Formation	399428	7892168	TENNANT CREEK	
Unnamed	2690	Occurrence	MO	Hydrothermal	Bootu Formation	389430	7915370	HELEN SPRINGS	
W38RDH	2688	Occurrence	Prospect	Hydrothermal	Shillinglaw Formation	368980	7963170	HELEN SPRINGS	W38RDH: 3m @ 42.4% Mn
VICTORIA BASIN									
Battle Creek 1	2460	Occurrence	MO	Surficial enrichment	Battle Creek Formation	748731	8207462	VICTORIA RIVER DOWNS	
Battle Creek 2	2656	Occurrence	MO	Surficial enrichment	Battle Creek Formation	745431	8211862	VICTORIA RIVER DOWNS	

APPENDIX 3

Summary data on bauxite occurrences in the Northern Territory. MO = mineral occurrence.

BAUXITE

Name	Site Id	Size	Status	Model	Host Formation	MGA E	MGA N	250K Sheet Name	Comments
ARAFURA BASIN									
Able	2475	Medium	Prospect	Laterite type bauxite	Yirrkala Formation	686324	8761763	TRUANT ISLAND	4.7 Mt @ 47% Av.Al_2O_3 resource
Baker	2479	Small	Prospect	Laterite type bauxite	Yirrkala Formation	688624	8768863	TRUANT ISLAND	0.2 Mt @ 48% Av.Al_2O_3 resource
Dog	2476	Medium	Prospect	Laterite type bauxite	Yirrkala Formation	684724	8760363	TRUANT ISLAND	1.3 Mt @ 47% Av.Al_2O_3 resource
Easy	2472	Small	Prospect	Laterite type bauxite	Yirrkala Formation	676624	8747663	TRUANT ISLAND	0.8 Mt @ 45% Av.Al_2O_3 resource
Elcho North	2443	Occurrence	MO	Laterite type bauxite	Yirrkala Formation	594125	8687563	WESSEL ISLANDS	Untested
Elcho South	2681	Occurrence	MO	Laterite type bauxite	Yirrkala Formation	592325	8685263	WESSEL ISLANDS	Untested
Fox	2474	Small	Prospect	Laterite type bauxite	Yirrkala Formation	675624	8750563	TRUANT ISLAND	0.8 Mt @ 43% Av.Al_2O_3 resource
Red Cliff	2473	Small	Prospect	Laterite type bauxite	Yirrkala Formation	674624	8751963	TRUANT ISLAND	0.8 Mt @ 44% Av.Al_2O_3 resource
Sphinx Head	2477	Medium	Prospect	Laterite type bauxite	Yirrkala Formation	687424	8762463	TRUANT ISLAND	1.3 Mt @ 44% Av.Al_2O_3 resource
Truant Island	2478	Occurrence	MO	Laterite type bauxite	Undefined	698124	8709163	TRUANT ISLAND	
CARPENTARIA BASIN									
Cato Plateau	2313	Occurrence	Prospect	Laterite type bauxite	Yirrkala Formation	670126	8632164	GOVE	
Dhupuma	2670	Small	Prospect	Laterite type bauxite	Yirrkala Formation	698600	8631150	GOVE	35-70 Mt untested lateritic bauxite
Gove	2328	Large	Operating mine	Laterite type bauxite	Yirrkala Formation	701125	8640164	GOVE	Past production: 155 Mt @ 50.5% Al_2O_3. Resource: 176 Mt @ 47% Av.Al_2O_3
Milingimbi	2616	Occurrence	Prospect	Laterite type bauxite	Yirrkala Formation	490426	8636563	MILINGIMBI	
Umbakumba	2445	Occurrence	MO	Laterite type bauxite	Walker River Formation	693825	8468265	GROOTE EYLANDT	
MONEY SHOAL BASIN									
Araru Point	2480	Occurrence	MO	Laterite type bauxite	Bathurst Island Formation	815628	8760160	MELVILLE ISLAND	2.4 Mt @ 35-40% Al_2O_3 resource
Cache Point	2481	Occurrence	MO	Laterite type bauxite	Van Diemen Sandstone	715129	8744160	MELVILLE ISLAND	
Croker Island	2490	Occurrence	MO	Laterite type bauxite	Bathurst Island Formation	235627	8780162	COBOURG PENINSULA	0.66 Mt @ 30%+ Av.Al_2O_3 resource
Danger Point	2486	Occurrence	MO	Laterite type bauxite	Bathurst Island Formation	209627	8763662	COBOURG PENINSULA	
Goolambinni	2482	Occurrence	MO	Laterite type bauxite	Van Diemen Sandstone	665630	8736160	MELVILLE ISLAND	
Lingi Point	2483	Occurrence	MO	Laterite type bauxite	Bathurst Island Formation	811128	8756160	MELVILLE ISLAND	
Midjari Point	2484	Occurrence	MO	Laterite type bauxite	Bathurst Island Formation	824128	8762160	MELVILLE ISLAND	
Mount Roe	2334	Occurrence	MO	Laterite type bauxite	Bathurst Island Formation	181027	8726363	COBOURG PENINSULA	
Smith Point	2487	Occurrence	MO	Laterite type bauxite	Bathurst Island Formation	191127	8766162	COBOURG PENINSULA	
Snake Bay	2485	Occurrence	MO	Laterite type bauxite	Van Diemen Sandstone	679129	8738160	MELVILLE ISLAND	
Turtle Point	2488	Occurrence	MO	Laterite type bauxite	Bathurst Island Formation	184127	8757662	COBOURG PENINSULA	
Vashon Head	2489	Occurrence	MO	Laterite type bauxite	Bathurst Island Formation	828503	8764146	COBOURG PENINSULA	9.7 Mt @ 46% Al_2O_3 resource

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