GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

RECORD 1989/2

EXPLANATORY NOTES ON THE BALFOUR DOWNS 1:250 000 GEOLOGICAL SHEET WESTERN AUSTRALIA (SECOND EDITION)

by

I.R. Williams

DEPARTMENT OF MINES
WESTERN AUSTRALIA

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MINISTER FOR MINES
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D. R. Kelly

DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
Phillip E. Playford

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The Director
Geological Survey of Western Australia
100 Plain Street
EAST PERTH, WESTERN AUSTRALIA 6004
Telephone (09) 222 3168

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By I. R. Williams

INTRODUCTION

The BALFOUR DOWNS* 1:250 000 geological sheet (SF/51-9) lies between latitudes 22°00'S and 23°00'S and longitudes 120°00'E and 121° 30'E and is named after a large pastoral lease in the southeast of the sheet.

There are no towns but people reside at four cattle station homesteads - Balfour Downs, Ethel Creek, Noreena Downs and Mount Divide. Parts of the Roy Hill, Bonnie Downs, Wandanya, and Billinooka cattle station leases extend onto the sheet along the northern, western and southern boundaries. The land east of the Oakover River is unoccupied.

The graded Great Northern Highway, crosses the northwest corner and also runs, for a short distance, along the western boundary west of Ethel Creek homestead. It links the iron-ore mining town of Newman, 48 km to the southwest, to Nullagine, a small mining/pastoral centre, 14 km north of BALFOUR DOWNS. A graded road to the Jigalong Community traverses the southern margin as far east as Bridgy Well. Graded access roads to homesteads, station tracks and mostly abandoned bulldozed mining and mineral-exploration tracks provide reasonable access to most of the region west of the Oakover River. East of the Oakover River a well-defined track links Old Mia Well (Old Talawana homestead) to Wells 23 and 24 on the Canning Stock Route and to Windy Corner in the Gibson Desert. A

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* 1:250 000 scale sheet names are printed in capitals to avoid confusion with similar place names.

poor, sandy track extends eastwards from Christies Crossing on the Oakover River past Bocrabee Hill to the Rudall River. A few mining-exploration tracks occur in the Canning Well and Enacheddong Creek areas. The abandoned No 1 Vermin Proof Fence crosses BALFOUR DOWNS from south to north. In many places the fence has completely disappeared.

Field mapping for the second edition of BALFOUR DOWNS was carried out in 1983 (R.J. Chin and I.R. Williams) and 1984 (I.R. Williams). It was plotted on 1:40 000 air-photographs flown in 1972 by the Western Australia Lands and Surveys Department (now called Department of Land Administration) and compiled on Commonwealth National Mapping 1:100 000 scale base sheets.

Most of the sheet was covered in detail except for the sand-dune and hilly country east of the Oakover River, the strongly dissected headwater region southwest of the Davis River, and the hilly Mount McKay area. These areas were mapped on widely spaced cross-country traverses. The rough granite country around Mount Maggie and complex dune areas southeast of the Talawana - Windy Corner track were mainly mapped by photo-interpretation.

PREVIOUS INVESTIGATIONS

A brief description of early exploration and geological investigations up to 1963 can be found in de la Hunty (1964). Subsequent publications on BALFOUR DOWNS have been directed towards reappraisals of the manganese deposits (de la Hunty 1965a, 1966, Giesecke 1966, Blockley 1975b) and attempts at regional correlation or integration of the several Precambrian sedimentary sequences previously mapped. (de la Hunty 1966, Daniels 1975, Goode 1981, Goode and Hall 1981, Chuck 1984, Muhling and Brakel 1985).

CLIMATE, VEGETATION, PHYSIOGRAPHY

The climate is transitional from desert with a summer rainfall ranging up to 300 mm in the east, to semi-desert-tropical with a mostly summer rainfall (over 300 mm) in the northwest corner (Beard 1975). The summers are hot with a mean annual maximum temperature of 34°C and winters are mild with a mean annual minimum of 19°C.

BALFOUR DOWNS straddles the boundary between the Pilbara and Little Sandy Desert natural regions (Figure 1). These regions in turn correspond to the Fortescue and Keartland Botanical districts (Beard 1975).

Spinifex (*Triodia* sp., Plectrachne) is widespread. It covers the sandridges of the Little Sandy Desert and is associated with mixed shrubs (*Acacia* and *Eucalyptus* sp) in the interdunal areas. Shrub and open-tree steppe (*Eucalyptus* and *Acacia* sp) with spinifex typifies the northern half of BALFOUR DOWNS west of the sand-dune country. The southern half, occupied by the Fortescue River valley and the upper reaches of the Oakover River, has a variety of vegetation regimes. These include spinifex-dominated sand plains with scattered *Eucalyptus* sp., bare open 'buckshot' (ironstone pebble) plains with mulga groves (*Acacia* sp) and low mulga woodlands and tree savanna (*Eucalyptus microtheca*) on gilgai plains. Detailed descriptions of the flora can be found in Beard (1975).

Elevations range from 610 m ASL near Mount Trew to less than 340 m in the beds of the Davis and Oakover Rivers where they pass northwards onto NULLAGINE. The major drainage divide between the Fortescue River valley and headwaters of the Oakover River comprises a broad zone of hills with elevation exceeding 500 m (Fig. 1).

Although hills and breakaways are widespread on BALFOUR DOWNS, relief is generally low, ranging from 100 to 150 m.

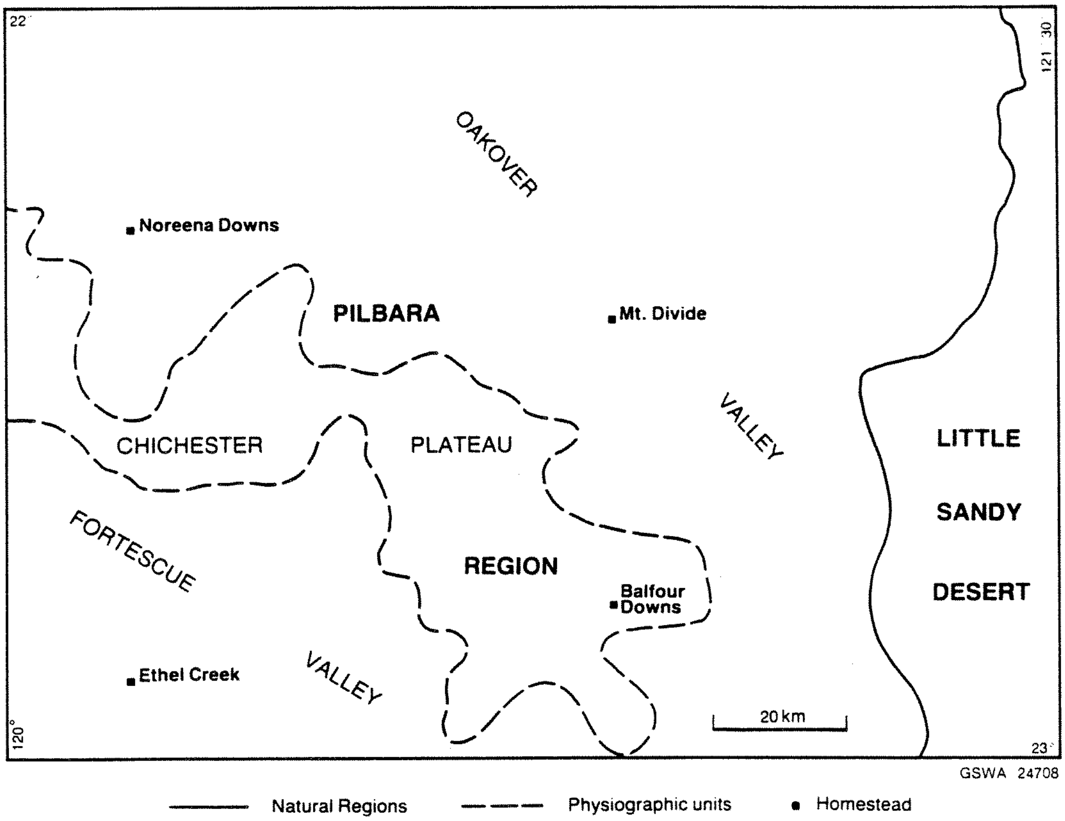

Figure 1. Natural Regions, BALFOUR DOWNS

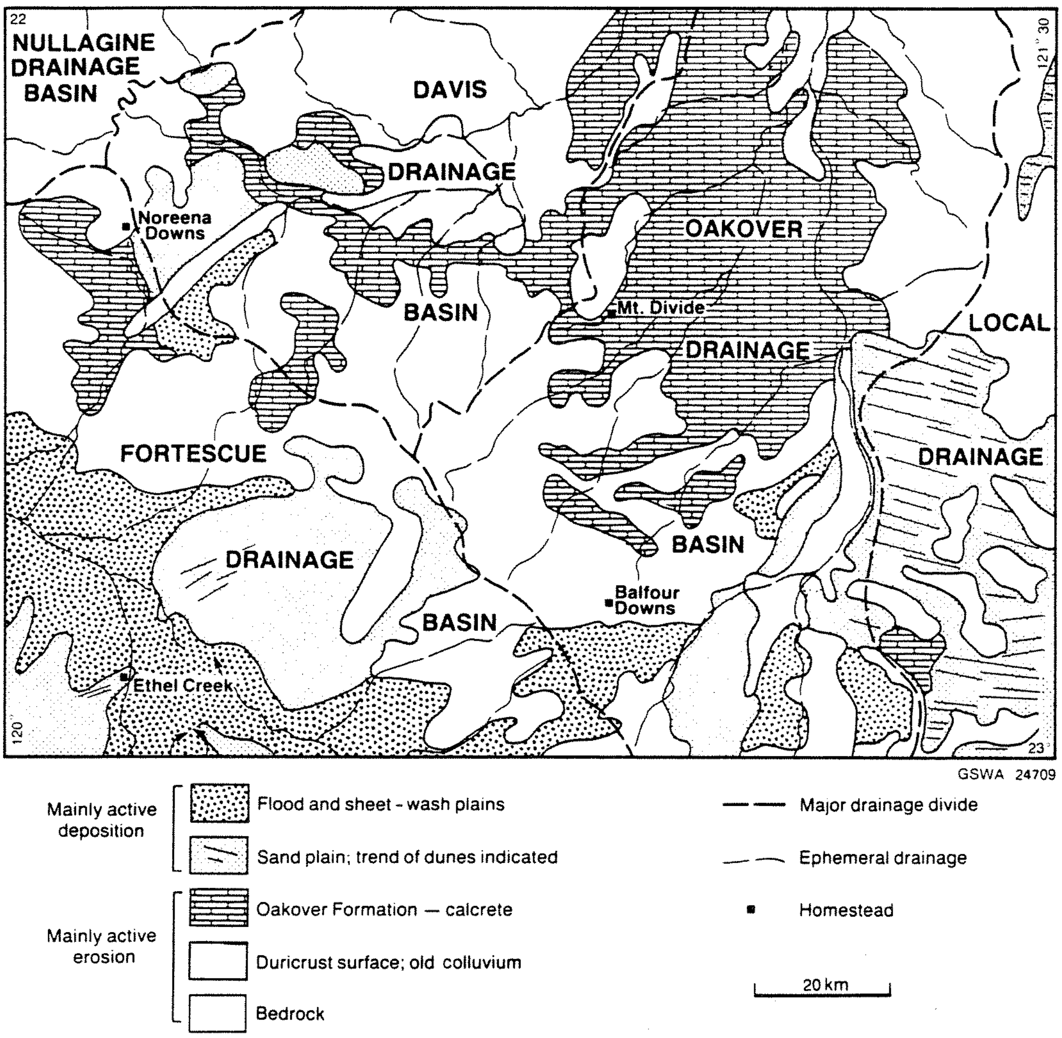

Figure 2. Physiographic sketch map, BALFOUR DOWNS

A maximum relief of over 200 m is reached in rugged hills southeast of Shag Pool on the Davis River. Prominent hills which rise above the generally subdued landscape include Mount Cooke (541 m ASL), Mount Lewin (572 m) Mount McKay (578 m) and Mount Trew (584 m). A discussion of the main drainage basins can be found in de la Hunty (1964).

A physiographic sketch map (Figure 2) outlines the main morphological units. These can generally be divided into two main groups. The first group includes regions of alluvium and adjacent areas of little or no erosion. It mainly comprises the broad Fortescue River drainage where the main channels have a gradient of less than 1:1600. It includes the Fortescue River flood plains - braided channels, levees, gilgai and gravel (buckshot pebble) plains - and adjacent, low slope, sheet-wash pediments. A small area of sheet-wash, claypans and sand dunes east of the Wadara Range in the Oakover River drainage is included in this category. Sand plains and sand dune terrains (longitudinal and chain dunes) that are devoid of defined drainage channels are also included in this group.

The second group comprises regions of moderate to strong erosion. It is typified by scarp retreat, dissected hills and mesas capped with Tertiary Oakover Formation, lateritized and silcretized duricrust including the Hamersley surface of Campana and others (1964), dissected semi-consolidated older colluvium and incised sandy stream channels. The uplift which caused this drainage rejuvenation is thought to have occurred in the middle Tertiary (Jutson 1950, p. 205).

The stripping of the duricrusted surface is mainly confined to the Oakover River and its tributaries. The average gradient along the Davis River (1:625) and the Oakover River (1:654) is 2.5 times greater than the Fortescue River drainage on BALFOUR DOWNS. The duricrusted surface appears to dip gently beneath the recent alluvial deposits of the Fortescue flood plain.

PRECAMBRIAN ROCKS

BALFOUR DOWNS covers part of five Precambrian tectonic units: the Pilbara Craton (Gee, 1979); Hamersley Basin (Trendall, 1968); Bangemall Basin (Daniels and Horwitz, 1969); Paterson Orogen (previously called the Paterson Province by Daniels and Horwitz, 1969); and the newly recognized late Precambrian Savory Basin (Williams and Tyler, in press).

Lithostratigraphic correlation in the region has been controversial and subject to much debate over the last two decades (Button, 1976; Williams and others, 1976; Goode, 1981; Goode and Hall, 1981; Chuck, 1984; and Muhling and Brakel, 1985; see Table 3).

The sequential production of BALFOUR DOWNS (1st Edition, de la Hunty, 1964) followed by adjoining 1:250 000 sheets, ROY HILL (McLeod and de la Hunty, 1966), NULLAGINE (Hickman, 1978), GUNANYA (Williams and Williams, 1980), RUDALL (Chin and others, 1980) and PATERSON RANGE (Chin and others, 1982) has seen continual modifications, readjustments, and realloctions of the stratigraphic units within and between the major tectonic units of the region. Such changes have been summarized in the following tables.

Table 1 shows the changes in stratigraphy from that on the first edition (1964) of BALFOUR DOWNS. Table 2 is a stratigraphic correlation chart comparing the stratigraphy of the Fortescue and lower Hamersley Groups on BALFOUR DOWNS with the adjoining ROY HILL and NULLAGINE 1:250 000 sheets. Finally Table 3 illustrates recent changes in thought on the correlation of the Managnese Group (de la Hunty, 1963) with other units.

TABLE 1

COMPARATIVE PRECAMBRIAN STRATIGRAPHY
BALFOUR DOWNS

de la Hunty (1964)		This survey 1983-84	
	Bocrabee Sandstone	Coondra Formation	SAVORY GROUP
		Watch Point Formation	SAVORY GROUP
		--------Unconformity--------	
		Isdell Formation	YENEENA GROUP
		Choorun Formation	YENEENA GROUP
		Yandanunyah Formation	YENEENA GROUP
		Brownrigg Sandstone	YENEENA GROUP
		Waroongunyah Formation	YENEENA GROUP
	Googhenama Conglomerate	Googhenama Conglomerate	YENEENA GROUP
--------Unconformity--------		--------Unconformity--------	
MANGANESE GROUP	Noreena Shale Balfour Shale	Whitewood Formation	MANGANESE * GROUP
		Balfour Formation	MANGANESE * GROUP
		Enacheddong Dolomite	MANGANESE * GROUP
		Stag Arrow Formation	MANGANESE * GROUP
	Bee Hill Sandstone Coondoon Conglomerate	Woblegun Formation	MANGANESE * GROUP
		Coondoon Formation	MANGANESE * GROUP
		--------Unconformity--------	
	Pinjian Chert Breccia	Pinjian Chert Breccia	
--------Unconformity--------		--------Unconformity--------	
	Carawine Dolomite	Carawine Dolomite	HAMERSLEY GROUP
	Lewin Shale	Marra Mamba Iron-Formation	HAMERSLEY GROUP
		Jeerinah Formation	FORTESCUE GROUP
		Roy Hill Shale Member	FORTESCUE GROUP
		Warri Member	FORTESCUE GROUP
		Unnamed volcanic member	FORTESCUE GROUP
		Woodiana Sandstone Member	FORTESCUE GROUP
	Little de Grey Lava (in part) Tumbiana Pisolite	Nymerina Basalt	FORTESCUE GROUP
		Tumbiana Formation	FORTESCUE GROUP
		Meentheena Carbonate Member	FORTESCUE GROUP
		Mingah Tuff Member	FORTESCUE GROUP
	Little de Grey Lava (in part) Beaton Creek Conglomerate	Kylena Basalt	FORTESCUE GROUP
		Hardey Sandstone	FORTESCUE GROUP
		Mount Roe Basalt	FORTESCUE GROUP

* Subsequent remapping of these rocks on the adjoining ROBERTSON showed that they could be correlated with the Collier Subgroup of the Bangemall Group. The Muhling and Brakel proposal of Manganese Subgroup should therefore now be adopted.

TABLE 2

CORRELATION CHART BETWEEN BALFOUR DOWNS AND ADJOINING NULLAGINE AND ROY HILL FOR THE FORTESCUE GROUP AND LOWER UNITS OF THE HAMERSLEY GROUP

ROY HILL (1966)		BALFOUR DOWNS (1983-84)	NULLAGINE (1978)	
Wittenoom Dolomite		Carawine Dolomite	Carawine Dolomite	HAMERSLEY GROUP
Marra Mamba Iron Formation		Marra Mamba Iron Formation		
Jeerinah Formation		Jeerinah Formation		
Roy Hill Shale Member		Roy Hill Shale Member		
Warri Member		Warri Member	Lewin Shale	
		Unnamed volcanic member		
Woodiana Sandstone Member		Woodiana Sandstone Member		
Maddina Basalt Member	MOUNT JOPE VOLCANICS		Maddina Basalt	
Kuruna Siltstone Member		(absent)	Kuruna Siltstone	
Nymerina Basalt Member		Nymerina Basalt	Nymerina Basalt	
Tumbiana Pisolite Member		Tumbiana Basalt	Tumbiana Formation	
		Meentheena Carbonate Mbr	Meentheena Carbonate Mbr	FORTESCUE GROUP
		Mingah Tuff Member	Mingah Tuff Member	
Kylena Basalt Member		Kylena Basalt	Kylena Basalt	
		Hardey Sandstone	Hardey Sandstone	
		Mount Roe Basalt	Mount Roe Basalt	

TABLE 3. LATE PRECAMBRIAN STRATIGRAPHIC CORRELATION - HISTORICAL COMPARISON 1975 TO 1986 - MANGANESE GROUP

G.S.W.A. MEMOIR 2 1975	HORWITZ 1975	BUTTON 1976	WILLIAMS ET AL 1976	GOODE 1981	CHUCK 1984	MUHLING & BRAKEL 1985	BALFOUR DOWNS 2ND ED. 1986
			Calyie Sandstone — BANGEMALL GROUP	Calyie Sandstone — BANGEMALL	Calyie Sandstone — BANGEMALL	Calyie Sandstone — BANGEMALL	Savory Group
			--uncon--	---uncon--	---uncon---		----uncon---
Bocrabee Sandstone Googhenama Conglom. — BANGEMALL	Bangemall Group	Bocrabee Sandstone Googhenama Conglom. — BANGEMALL GROUP	Yeneena Group	Yeneena Group — GROUP	Yeneena Group — GROUP	Manganese Sub Group — GROUP	Yeneena Group
	--uncon-----	--uncon----	----uncon-----	---uncon----	---uncon-----	----uncon----	----uncon----
Manganese Group — GROUP	Manganese Group — WYLOO GROUP	Manganese Group — WYLOO GROUP	Manganese Group — UNASSIGNED	Manganese Sub Group — WYLOO GROUP	Manganese Sub Group	Yeneena Group	Manganese Group * — BANGEMALL GROUP

* Subsequent remapping of these rocks on the adjoining ROBERTSON showed that they could be correlated with the Collier Subgroup of the Bangemall Group. The Muhling and Brakel proposal of Manganese Subgroup should therefore now be adopted.

The terms Archean and Proterozoic are not used on BALFOUR DOWNS and therefore the prefix letters on the Precambrian rock symbols are derived from the lithostratigraphic units (i.e. named group, formation or lithology). Igneous rock names follow the recommendations of Streckeisen (1967).

PILBARA CRATON

Igneous and metamorphic rocks of the Pilbara Craton occupy only a small part of BALFOUR DOWNS, but the distribution of inliers suggests that the craton underlies most of the Sheet. The main outcrop occurs in the northwest where the Kurrana Batholith (Hickman, 1983), with a thin selvage of Mosquito Creek Formation (Hickman, 1975) extend about 25 km southwards from the northern boundary of the Sheet. Several small basement inliers occur to the southeast and, from northwest to southeast are named, the Rat Hill, Turkey and Rooney Inliers. These inliers are predominantly metasedimentary rocks which resemble the Mosquito Creek Formation. Farther southeast, the Springo, Cooninia and Billinnooka Inliers comprise post-tectonic granitoid rocks. All these inliers and the Kurrana Batholith are unconformably overlain by lower units of the Fortescue Group. The Billinnooka Inlier is also uncomformably overlain, by the Manganese Group.

The southern end of the Gregory Granitic Complex (de Laeter and others, 1977) is exposed in the northeast corner of BALFOUR DOWNS. It is unconformably overlain by the Yeneena Group (Paterson Orogen). The age and tectonic relationship between the Gregory Granitic Complex and the Pilbara Craton has been discussed by de Laeter and others (1977) and Hickman (1983).

Metasedimentary and minor mafic and ultramafic rocks

Metasedimentary and minor metamorphosed mafic and ultramafic igneous rocks consist of low-greenschist to amphibolite facies assemblages, most of which exhibit retrogressive sericitization and chloritization.

The metasedimentary rocks can be divided into three groups. The first group, form abundant xenoliths and pendants within the Kurrana Batholith (Hickman, 1983) 15 to 20 km northwest of Noreena Downs homestead, 3 km north of Kurrana Well and north of Sunday Hill. Only the larger xenoliths and pendants are shown on BALFOUR DOWNS. The main rock types are quartzite, fuchsite quartzite, quartz-muscovite-(sillimanite) schist (all Sq), and banded quartz magnetite rock and chert (both Si). They exhibit middle- or upper-amphibolite facies metamorphism and have a complex history with at least one metamorphic event in common with the enclosing gneisses.

The second group of metasedimentary rocks is the Mosquito Creek Formation (Hickman, 1978) which extends southwards from adjacent NULLAGINE. The main outcrop forms a thin wedge in faulted contact with the northwest margin of the Kurrana Batholith. The Mosquito Creek Formation is unconformably overlain on its northwestern side by the Fortescue Group. A second small exposure of Mosquito Creek Formation occurs on the northern boundary of BALFOUR DOWNS, 3 km northeast of Bubbawana Well.

The Mosquito Creek Formation consists of brown-weathering, grey-blue pelitic and psammitic schists and phyllites, (GCm) in greenschist facies with a prominent quartzite (Sq) and/or red and white banded chert (GCmx) at or near the base. The formation has been interpreted as a thick succession of psammitic and pelitic turbidites (Hickman, 1978). On BALFOUR DOWNS shearing and metamorphism have largely obliterated bedding. The formation contains folded pegmatite dykes close to the faulted contact with the Kurrana Batholith.

The third group of metasedimentary rocks crops out in the Rat Hill, Turkey and Rooney Inliers. These rocks are poorly exposed, deeply weathered and are typically covered by white quartz rubble.

The Rat Hill Inlier consists of a uniform sequence of grey-blue meta-quartz-feldspar wacke, meta-siltstone and quartz-mica schist (Ap) which was metamorphosed in the upper greenschist facies. Subsequent retrograde metamorphism has produced ubiquitous sericite which is, in places, pseudomorphic after porphyroblasts of alumina-silicate minerals.

Lenticular bodies of corundum-muscovite-diaspore-rutile rock (sr) form prominent outcrops 2 km southwest of Rat Hill. The diaspore is pale grey-blue and coarsely crystalline and occurs in veins and joint fillings in the corundum-rich parts of the lenses. These lenses occur with quartz-mica (-andalusite?) schist close to meta-gabbro intrusions and their origin is uncertain.

The Turkey and Rooney Inliers consist of highly micaceous schist, mainly a quartz-muscovite(biotite)-assemblage, and prominent quartzite. The schist was metamorphosed to the middle greenschist to low amphibolite facies and muscovite is more common than at Rat Hill. However retrograde metamorphism has produced abundant sericite and similar pseudomorphs after alumina-silicates to those seen at Rat Hill.

This third group of metasedimentary rocks resembles the Mosquito Creek Formation. However, the overall primary fine grained nature of the rocks suggest they are a more distal assemblage. All three inliers are intruded by scattered pegmatites of at least two generations. The Rat Hill Inlier also contains some small irregularly shaped, post-tectonic monzo and syenogranite intrusions.

Only minor mafic and ultramafic rocks are intercalated with or intrude the metasedimentary rocks on BALFOUR DOWNS. Serpentinized peridotite (uc) intrudes the fault between the Kurrana Batholith and the Mosquito Creek Formation west of Cajeput Creek. Small pods of tremolite-chlorite-talc rock (uu) (after peridotite) occur in the Mosquito Creek Formation and in the Turkey Inlier. Meta-pyroxenite (ux) and tremolite-chlorite-talc pods are fairly abundant as xenoliths within the monzogranite and granodiorite gneiss terrain (gmx) of the Kurrana Batholith; pods of fine-grained banded amphibolite also form xenoliths in this terrain.

Amphibole-plagioclase schist (ba) forms several long, narrow intercalations in the Mosquito Creek Formation along the northern boundary of BALFOUR DOWNS. The schist contains fine-grained, dark hornblende, plagioclase and quartz with accessory sphene, apatite and some garnet. The plagioclase is oligoclase to andesine. These schists may have originated as basalts (Hickman, 1978).

A poorly exposed, metamorphosed layered gabbroic intrusion (dl), at least 10 km long and over 1 000 m thick, lies 2 km west of Rat Hill. It is a gently arcuate body which appears to be conformable with the regional schistosity. Large-scale compositional layering ranges from granophyric gabbro through quartz gabbro, melanogabbro to coarse - grained actinolite-chlorite rock (metapyroxenite). The metamorphic grade is middle to upper greenschist facies.

Cumulate textures are present but the primary way-up of the layering could not be determined with certainty.

Granitoid rocks

The exposed Pilbara Craton on BALFOUR DOWNS is dominated by granitoid rocks which occur in the Kurrana Batholith (Hickman, 1983), the Gregory Granitic Complex (Hickman, 1975, 1978, 1983), and in the Springo, Cooninia and Billinnoka Inliers.

Kurrana Batholith

The Kurrana Batholith is a composite body of biotite monzogranite and granodiorite gneiss (gm) with xenoliths of metasedimentary and metamorphosed mafic and ultramafic rocks (gmx) concentrated into zones: schistose, gneissose and well foliated biotite monzogranite and syenogranite (gg); and a large body of post-tectonic biotite-muscovite monzogranite and syenogranite (gc) called the Bonnie Downs Granite (Hickman 1983).

The biotite monzogranite and granodiorite gneiss occupies the southern fringe of the Kurrana Batholith between Quartz Well and Russian Jack Well. Extensive outcrops also occur in the Kurrana Well and Sunday Hill area. The granodiorite gneiss is medium grained and generally has a strong biotite lineation. The strong deformation has produced a flaser fabric in some places. Deformed granitic veins in the gneiss indicate that some partial melting occurred and the gneiss is partly retrogressed from amphibolite to greenschist facies.

The xenolith-rich zones have been interpreted as either marginal zones of the batholith or root zones of synclinal greenstone belts (Hickman, 1983).

A preliminary Sm-Nd T_{CHUR} model age of 3153 ±32 Ma (T_{MORB} 3387± 28 Ma) have been obtained from a lineated grandiorite gneiss collected from the Haystack Well area.

The schistose, gneissose and strongly foliated biotite monzogranite and syenogranite form discrete bodies and appear to be slightly younger than the gm unit. Deformation was locally very strong and a flaser fabric developed in rocks adjacent to the fault contact between the Kurrana Batholith and Mosquito Creek Formation on the northwestern margin of the batholith. The rocks are medium to coarse, even-grained and well foliated. Foliated bodies of this type occur in the Kujebookinah Bore area, 4 kms north of Kurrana Bore, along the northwestern margin of the Kurrana Batholith and 4 kms northwest of Sunday Hill.

Bonnie Downs Granite

The Bonnie Downs Granite is a post-tectonic, coarse grained to porphyritic syeno- and monzogranite phase of the Kurrana Batholith, and has been described by Hickman, (1983). It contains more muscovite than the older granitoid rocks, microcline dominates over plagioclase, plagioclase is more albitic and fluorite occurs as an accessory.

A sample collected from the Bonnie Downs Granite near Dingo Well gave a preliminary Sm-Nd T_{CHUR} model age of 3166 ± 33 Ma (T_{MORB} of 3419 ± 28 Ma).

The Kurrana Batholith appears to be a structural dome. (Hickman, 1983). The regional foliation and lineations in the granitoid rocks, and bedding in the overlying Fortescue Group all dip away from the northerly trending axis of the batholith. All the granitoid rocks have been subjected to late-stage low-grade greenschist facies metamorphism with the growth of pumpellyite.

The Springo, Cooninia and Billinnooka Inliers of post-tectonic granitoid appear to have been block faulted into the Fortescue Group rocks and not to have acted as basement domes during deposition of those rocks.

The granitoid rocks of the inliers range from coarse grained equigranular to porphyritic biotite monzogranite in the large Cooninia Inlier, to even-grained biotite muscovite monzogranite in the Springo inlier, and leucocratic muscovite-biotite monzo- and syenogranite in the Billinnooka Inlier. In most samples biotite is strongly chloritized, and, in the Cooninia Inlier, fluorite occurs as an accessory. All these rocks appear to have been subjected to low-grade greenschist facies metamorphism.

Although bold joint-controlled outcrops and tors occur in the Cooninia and Billinnooka Inliers, most of the granitic rock is weathered and poorly exposed. Vein quartz is abundant and finer grained monzogranite, syenogranite and rare pegmatite are late-stage intrusions.

Monzogranite samples collected 7.5 km east-southeast of Springo Bore (Site 1) and 10 kms east of Limestone Bore (Site 2) in the Cooninia Inlier yield a combined Rb-Sr whole rock isochron of 2644 ± 57 Ma (initial ratio 0.7053 ± 0.0010). Site 1 also yielded a Sm-Nd ^{T}CHUR model age of 3038 ± 28 Ma(^{T}MORB 3273 ± 24 Ma) and site 2 yielded a Sm-Nd ^{T}CHUR model age of 3035 ± 26 Ma (^{T}MORB 3267 ± 23 Ma). The Billinnooka monzogranite gave a Sm-Nd ^{T}CHUR model age of 2976 ± 27 Ma (^{T}MORB 3225 ± 24 Ma).

Gregory Granitic Complex

The Gregory Granitic Complex (Hickman, 1975, 1978, 1983) extends about 11 km into the northeast corner of BALFOUR DOWNS from adjacent NULLAGINE. It is a narrow (10 km wide) zone of strongly deformed granitoid rocks which is thought to form the eastern margin of the Pilbara Craton. Some rocks resemble the schistose and gneissose biotite monzogranite and syenogranite (gg) of the Kurruna Batholith but others are distinctive and include mylonitized hornblende augen gneiss (ga) with minor sphene. These rocks are intruded by a foliated porphyritic felsic rock consisting of large rounded potash feldspars set in a very fine grained matrix composed of quartz, potash feldspar and Fe/Ti oxides. De Laeter and others (1977) obtained a whole-rock Rb-Sr istopic age of 2651 $\pm$ 60Ma from the gneissic syenogranite and monzogranite component of the complex. The western margin of the Gregory Granitic Complex is a fault and to the south and east the complex is unconformably overlain by the Yeneena Group.

Structure

Hickman (1983) has described the detailed structural history of the Pilbara Craton (originally called Block). He recognizes four main deformation episodes (D_1 - D_4) prior to the deposition of the basal Fortescue Group of the Hamersley Basin (about 2800 Ma). Because outcrops of the Pilbara Craton on BALFOUR DOWNS are restricted to a series of small inliers, it is uncertain how their structure fits into this deformational history. However it is evident that greenstone xenoliths (pelitic and mafic schists) within the Kurrana Batholith were already deformed and metamorphosed (D_1) before the intrusion of this batholith. Subsequently both the greenstone remnants and granitic rocks were folded together (D_2).

Hickman (1983) attributed the strong foliation in the granitoid rocks to diapiric movement of the granitoid bodies during late deformation. The D_2 event is associated with greenschist to amphibolite facies metamorphism.

A tectonic slide mapped on NULLAGINE (Hickman, 1983) between the Mosquito Creek Formation and the Kurrana Batholith, extends southwest onto BALFOUR DOWNS. Serpentine pods lie in this shear zone. A similar, parallel, slide, marginal to a thin wedge of Mosquito Creek Formation, lies 6 km north of Kujebookinah Bore. Both these slides belong to the D_2 event.

The pelitic schists in the Rat Hill, Turkey and Rooney Inliers show a complex history of deformation and metamorphism. A thick sequence of fine grained sedimentary rocks was intruded by gabbroic sills, and then deformed, metamorphosed and intruded by granitoid rocks. Following the granitoid intrusion the entire sequence was refolded and subjected to further low-grade metamorphism. Post-tectonic granitoid rocks were then emplaced. This sequence of events resembles the sequence described by Hickman (1983) from the Pilbara Craton.

Minor intrusive rocks

Several mafic dyke suites (do, d_1, d_2) intrude both the granitoid and layered rocks of the Pilbara Craton and are unconformably overlain by the Fortescue Group.

The most prominent mafic dyke (do), the Cajuput dyke (Hickman, 1983), crosses the northwest corner of BALFOUR DOWNS along the northwest margin of the Kurrana Batholith. The dyke intrudes both the Mosquito Creek Formation and schistose biotite monzogranite (gg) of the Kurrana Batholith. The Cajuput dyke trends north-northeast and has a maximum width of 1 000 m, 2 km south of Daylight Rock Hole. The dyke is gabbroic and has a distinct contact aureole. The dyke margins contain quartz xenocrysts and country-rock xenoliths.

Similar large north-northeast trending gabbro dykes occur 23 km east of the Cajuput dyke and 3 km west of Bubbawana Well in the Kurrana Batholith and 9 km east of Limestone Bore in the Cooninia Inlier. This group of mafic dykes is genetically related to the Black Range Suite (Embleton, 1978; Hickman, 1983).

HAMERSLEY BASIN

On BALFOUR DOWNS, rocks of the Hamersley Basin comprise volcanic and clastic rocks of the Fortescue Group and the lowest units of the Hamersley Group. In the southeast they are either faulted against, or unconformably overlain by, the Manganese Group and in the northeast they are unconformably overlain by the Yeneena Group.

Fortescue Group

The Fortescue Group (MacLeod and others, 1963) rests with marked angular unconformity on eroded and weathered granitoid and metasedimentary rocks of the Pilbara Craton. The stratigraphic sequence and lithologies of the Fortescue Group are summarized in Table 4.

Although the Mount Roe Basalt is the oldest unit in the Fortescue Group, the unit which directly overlies the Pilbara Craton varies from place to place, suggesting the existence of considerable basement relief in some places and the presence of growth faults in others. Near Quartz Well on the western margin of the Kurrana Batholith the Nymerina Basalt onlaps the basement, suggesting a basement relief of at least 1 500 metres. Seven km west of Sunday Hill a similar onlap of Nymerina Basalt is attributed to the presence of a growth fault.

TABLE 4. PRECAMBRIAN STRATIGRAPHY BALFOUR DOWNS

AGE Ma	TECTONIC UNIT	GROUP	FORMATION	LITHOLOGY	ESTIMATED MAX. THICKNESS OR RANGE (METRES)
>800	SAVORY BASIN	SAVORY GROUP x	Coondra Formation	sandstone, minor conglomerate, wacke,	+ 800
			Watch Point Formation	siltstone, shale, minor sandstone	
	PATERSON OROGEN	YENEENA GROUP	Isdell Formation	dolomite, minor sandstone, conglomerate	1000
			Choorun Formation	sandstone, siltstone, shale	1200
890			Yandanunyah Formation	dolomite, siltstone, shale	80
			Brownrigg Sandstone	sandstone	350
			Waroongunyah Formation	dolomite, shale, siltstone, sandstone	250
			Googhenama Formation	conglomerate, sandstone	0 - 250
	BANGEMALL BASIN	MANGANESE GROUP	Whitewood Formation	sandstone, conglomerate	+ 250
			Balfour Formation	shale, minor siltstone, sandstone	1500
			Enacheddong Dolomite	dolomite, minor shale, chert	0 - 300
			Stag Arrow Formation	sandstone, siltstone, shale, conglomerate, dolomite, chert	500 - 1500
			Woblegun Formation	shale, minor sandstone,conglomerate, chert	0 - 280
1050			Coondoon Formation	conglomerate, sandstone, wacke, shale	0 - 100
		HAMERSLEY GROUP	Pinjian Chert Breccia	chert breccia	100
			Carawine Dolomite	dolomite, minor chert	150
			Marra Mamba Iron Formation	chert, iron formation, shale	30
	HAMERSLEY BASIN	FORTESCUE GROUP	Jeerinah Formation	shale, chert, jaspilite, mudstone, dolomite, minor basalt, felsic volcanics	200 - 800
			Roy Hill Shale Member	shale	120
			Warri Member	shale, dolomite, mudstone, jaspilite	300
			Unnamed volcanic member	pillow basalt, felsic tuff	0 - 300
			Woodiana Sandstone Member	sandstone, mudstone, conglomerate	60
			Nymerina Basalt *	basalt, minor tuff	2000
			Tumbiana	pisolitic tuff, carbonate, mudstone	80 - 200
2760			Kylena Basalt	basalt, minor tuff, carbonate	400 - 600
			Hardey Sandstone	sandstone, tuff, pisolitic tuff, conglomerate	0 - 350
			Mount Roe Basalt	basalt	0 - 350
2800					

* This formation may include some Maddina Basalt but the absence of the Kuruna Siltstone from BALFOUR DOWNS does not enable the distinction to be made.

x The formations in this group have been defined on the ROBERTSON 1:250 000 sheet.

The lowest units of the Fortescue Group have been deposited on the metasedimentary and metavolcanic components of the Pilbara Craton rather than the granitoid rocks (see also Trendall, 1984 p.254) while the most widespread unit at the base of the Group on BALFOUR DOWNS is the Kylena Basalt.

Evidence for pre-Fortescue Group weathering and silicification of bedrock can be seen 8 km northwest of Mount Chin Well where fresh Kylena Basalt is in contact with a dark jasperoidal chalcedony which caps a serpentine talc chlorite rock after peridotite.
The mineral assemblages in all the mafic rocks of the Fortescue Group indicate very low to low grade metamorphism. Smith and others (1982) place the basalts on BALFOUR DOWNS in a metamorphic transition region that ranges from a prehnite-pumpellyite-epidote zone in the north to a prehnite-pumpellyite epidote-actinolitic zone in the south. The static style of metamorphism is attributed to burial metamorphism that lies in the prehnite-pumpellyite to low greenschist facies.

Mount Roe Basalt (Fr)

The Mount Roe Basalt (Kriewaldt, 1964), the basal formation of the Fortescue Group, is mostly confined to a small, fault-terminated area along the eastern margin of the Rooney Inlier. A single small outcrop also occurs just west of Cajuput Creek beneath the Hardey Sandstone on the northwest margin of the Kurrana Batholith.

The formation consists of generally massive, fine to coarse-grained subaerial basalt with amygdaloidal and feldspar-phyric varieties.

Hardey Sandstone (Fh)

The Hardey Sandstone (MacLeod and others, 1983) conformably overlies the Mount Roe Basalt or rests unconformably on the metasedimentary or granitoid rocks of the Pilbara Craton.

The main exposures occur on the eastern side of Rooney Inlier, along the eastern margin of the Kurrana Batholith at Sunday Hill, and on the Mosquito Creek Formation along the northern boundary of the Sheet west of Cajuput Creek. The latter occurrence is the southern termination of the thick Hardey Sandstone at Nullagine, 14 km to the north on NULLAGINE.

Adjacent to the Rooney Inlier, the Hardey Sandstone consists of a basal, poorly sorted boulder conglomerate (Fh(c)) with chert blocks up to 4.5 m across set in a coarse-grained groundmass of subangular chert and quartz fragments. The boulder beds pass upwards to finer-grained better-sorted conglomerate, granule sandstone and wacke. The basal beds probably resulted from debris flows caused by an active fault line. The large chert blocks were derived from massive chert in the adjacent Rooney Inlier. Cross-bedding indicates current transport off the Rooney Inlier.

This coarse clastic component of the Hardey Sandstone is overlain by interbedded quartz-wacke, waterlain tuff and lapilli tuff. The volcanic component increases upwards in the sequence which probably accumulated in shallow water.

A similar but thinner sequence occurs at Sunday Hill. Coarse grained wacke and conglomerate overlain by bedded tuff and lapilli tuff, rest unconformably on granitoid rocks of the Pilbara Craton.

The Hardey Sandstone represents a period of epiclastic deposition during predominantly basaltic volcanic activity.

At a number of localities around the southern margin of the Kurrana Batholith and Cooninia Inlier, lenticular outcrops of coarse grained, clayey sandstone, grit, wacke and arkosic (now largely clay) breccia overlie the granitoid basement. These lenses which lie beneath the Kylena Basalt and appear to fill depressions in the eroded granitoid basement, have been equated with the Hardey Sandstone. They are thought to be derived directly from the weathered granitoid basement with crude beddings produced by solifluxion.

Kylena Basalt (Fk)

The Kylena Basalt (MacLeod and de La Hunty, 1966) conformably overlies the Hardey Sandstone and is the lowest extensive formation of the Fortescue Group on BALFOUR DOWNS. It is the lowest unit resting on the Rat Hill, Cooninia and Billinnooka Inliers.

The formation consists of massive, amygdaloidal dark-green to grey metabasalt with minor intercalations of thin-bedded tuff and carbonate lenses. Agglomerate (Fk(v)) occurs locally towards the top of the formation. Amygdales contain chlorite, chalcedony (agate), carbonate and stilpnomelane. The rocks are patchily altered with growth of carbonate and amphibole.

Most of the metabasalt has brecciated flow tops and columnar jointing and appears to have cooled subaerially although well-formed pillow structures occur in a small area, 2.5 km east of Dingo Well.

Tumbiana Formation (Ft)

The Tumbiana Formation (Hickman and Lipple, 1975) conformably overlies the Kylena Basalt and is 80-120m thick, slightly less than the type area on NULLAGINE (Hickman, 1983). Its distinctively striped photo-pattern makes it a good marker horizon. In northwest BALFOUR DOWNS, west of the Newman - Nullagine road, it is divided into the Meentheena Carbonate Member (Ftc) (Lipple, 1975) and Mingah Tuff Member (Ftt) (Lipple, 1975).

The formation is composed of metamorphosed lapilli tuff, bedded crystal, lithic and vitric tuff, quartz-wacke, tuffaceous siltstone, minor tuffaceous conglomerate and some intercalated basalt flows. The tuff is mostly basic but some is dacitic. Pisolitic beds are generally graded, with pisolites up to 10mm diameter, or cross bedded. Where the formation rests unconformably on granitic rocks it contains numerous fragments of the underlying rocks.

The Meentheena Carbonate Member comprises dark grey siliceous limestone and dolomite in the upper part of the formation west of the Newman - Nullagine road. North and south of Whatsamatta Well it contains scattered stromatolite bioherms 1 to 1.5 m high and up to 2 m wide. According to Grey (pers. comm.) the stromatolites show some similarities to Alcheringa narrina (Walter, 1972). Similar stromatolites were also found 4 km northwest of Mount Chin Bore and 3 km west of Wickham Well.

Nymerina Basalt (Fn)

The Nymerina Basalt (MacLeod and de la Hunty, 1966) conformably overlies the Tumbiana Formation and is the dominant basaltic formation of the Fortescue Group on BALFOUR DOWNS.

The Kuruna Siltstone (MacLeod and de la Hunty, 1966) conformably overlies the Nymerina Basalt on adjoining ROY HILL and NULLAGINE and forms a marker unit between the Nymerina Basalt and Maddina Basalt. The Kuruna Siltstone is not present on BALFOUR DOWNS and therefore it is not possible to distinguish the two basalt units. However the Maddina Basalt has been shown to lens out west of the Newman - Nullagine road on ROY HILL (MacLeod and de la Hunty, 1966) and therefore may not be present on BALFOUR DOWNS.

The Nymerina Basalt mainly comprises dark-green to grey, massive, vesicular and amygdaloidal meta-basalt. Some intercalated pyroclastic and silty epiclastic rocks (Fn(p)) occur west of Deep Well (Noreena Downs Station). A prominent feature of the upper part of the unit is the presence of very large amygdales (up to 50 cm across) which are mainly filled with pink to red carnelian-bearing agates. Amygdales also contain chlorite, carbonate, quartz and stilpnomelane.

Jeerinah Formation (Fj)

The Jeerinah Formation (Fj) (MacLeod and others, 1963) appears to rest conformably on the Nymerina Basalt. However there is an abrupt change from a volcanic to an epiclastic environment. The basalts are overlain by coarse-grained pebbly sandstone, lithic sandstone and conglomerate. In some areas a grey-green siliceous mudstone is at the base.

De la Hunty (1964) included the units of the Jeerinah Formation and the Marra Mamba Iron Formation in his Lewin Shale. Both the Jeerinah Formation and the Marra Mamba Iron Formation can now be distinguished on BALFOUR DOWNS as elsewhere in the Hamersley Basin and the term Lewin Shale is dispensed with.

The Jeerinah Formation has been subdivided into the Woodiana Sandstone Member, Warri Member and Roy Hill Shale Member. An unnamed volcanic unit separates the Woodiana Sandstone and Warri Members in places.

The Woodiana Sandstone Member (Fjo) (MacLeod and de la Hunty, 1966) occurs discontinuously at the base of the Jeerinah Formation. In places the unit is separated from the overlying Warri Member by the unnamed volcanic unit; elsewhere the Woodiana Sandstone Member is generally distinguishable from the Warri Member by its coarser grain size. The main components are grey-green lithic sandstone, quartz wacke and pebble conglomerate.

The Woodiana Sandstone Member occurs intermittently south from Cliff Well to 5 km west of Kullawarri Well. It is also present 9 km west of Holden Bore and 5 km east of Wandabah Well.

The unnamed volcanic member overlies the Woodiana Sandstone Member and forms a thick (up to 300 m) unit consisting mainly of basaltic pillow lava with a high carbonate content. Amygdales are not abundant and contain chlorite and carbonate. Bedded tuff is also intercalated with the basalt. The volcanic member was apparently deposited in a subaqueous environment which differs from the predominantly subaerial environment of the Fortescue Group basalt.

A fault-bounded inlier of intermediate lapilli tuff, fine-grained quartz porphyry and felsite, east of the Oakover River, is assigned to the Jeerinah Formation. These rocks are best exposed 10 km northeast of Canning Well and 4 km east of Enacheddong Water Hole.

The main component of the Jeerinah formation is the Warri Member (Fjw) (MacLeod and de la Hunty, 1966). It consists of numerous thin beds of mudstone, shale, ferruginous shale, chert, banded ferruginous chert, jaspilite and yellow, pink, green and grey dolomites. The dolomite beds (Fjw(d)) predominate in the upper part of the member around Mount McKay and Mount Lewin, where they contain numerous thin, blue-grey chert lenses and calcite veins parallel to bedding. The base of the Warri Member is a distinctive fine-grained grey-green mudstone which, in the absence of the Woodiana Sandstone Member, rests directly on the Nymerina Basalt.

The uppermost part of the Jeerinah Formation comprises the remarkably persistent Roy Hill Shale Member (Fjr) (MacLeod and de la Hunty, 1966). Although outcrop is poor it has a distinctive white photo-pattern formed by scree slopes beneath a ferruginous duricrust cap (Td) or ferrruginous podded cherts and shale of the Marra Mamba Iron Formation.

The Roy Hill Shale is composed of bleached and silicified white to grey shale (black and carbonaceous when fresh) containing rounded limonite nodules after pyrite.

Hamersley Group

The Hamersley Group (MacLeod and others, 1963) conformably overlies the Fortescue Group. Only the two lowest formations, the basal Marra Mamba Iron Formation and overlying Carawine Dolomite occur on BALFOUR DOWNS.

Marra Mamba Iron Formation (Hm)

The Marra Mamba Iron Formation (MacLeod and others, 1963) conformably overlies the Roy Hill Shale Member of the Jeerinah Formation. The formation crops out intermittently across BALFOUR DOWNS and is generally capped by thick (10 to 15 m) ferruginized duricrust (Td).

The formation consists of interbedded iron-stained greenish-yellow podded chert, shale, and jaspilite. It is thickest (60 m) northwest of Nine Mile Bore on Roy Hill station but gradually thins eastwards across the Sheet. About 10 m of podded chert and shale are exposed in cliff faces 8 km west-southwest of Bee Hill near the northern margin of BALFOUR DOWNS. Thin jaspilite beds occur at Mount Cooke and 4.5 km southwest of Sunday Hill.

Carawine Dolomite (Hc)

The Carawine Dolomite (Hickman, 1983; Carawine Dolomite Series, Maitland, 1919) conformably overlies the Marra Mamba Iron Formation. The Carawine Dolomite is a stratigraphic equivalent of the Wittenoom Dolomite (MacLeod and others, 1963) which lies to the west of BALFOUR DOWNS.

The presence of stromatolites and other features in the Carawine Dolomite which are absent from the Wittenoom Dolomite, suggest that the Carawine Dolomite was deposited in a more varied palaeoenvironment.

The Carawine Dolomite is a brown-weathering, well-bedded, crystalline grey dolomite with thin intercalated chert beds, nodules and veins. Shale is absent. A wide range of banded structures, ranging from stratiform laminations (stromatolitic or microbial mats) to large-scale bedding, are present. Unusual cementation fabrics are associated with the microbial mats and pseudomorphic fabrics (calcite after aragonite) are suggestive of evaporites.

Several episodes of silicification are evident in the dolomite. Late-stage fractures and joints generally contain cavities lined with quartz crystals. Silicified oncolites occur in dolomite 2 km east of the Tabuddabudda Copper Prospect.

Large areas of fresh dolomite are rare. The largest areas lie 1.5 km east of Old Mia Bore on Mount Divide Station and east of Googhenama Creek in the northeast corner of BALFOUR DOWNS. Elsewhere the presence of Carawine Dolomite is inferred from structural considerations and the widespread distribution of brecciated siliceous cap rock (Pinjian Chert Breccia) and associated surficial deposits.

Pinjian Chert Breccia

The Pinjian Chert Breccia (cb) (Noldart and Wyatt, 1962) overlies or replaces the Carawine Dolomite. The chert breccia forms casts of many large palaeokarst features where the pre-existing dolomite has been dissolved away. The chert breccia consists of angular chert fragments chaotically or crudely bedded, with a siliceous matrix locally enriched by iron and manganese oxides.

The chert breccia was a residual and replacement deposit on the Carawine Dolomite and was cemented by secondary silicification during subaerial exposure in the Precambrian and later in the late Tertiary to Recent. The Precambrian Pinjian Chert Breccia (cb) and later Tertiary siliceous capping (Tb) can both be regarded as a silicified duricrust or silcrete. Although steep bedding traces are recorded, these are interpreted as primary dips associated with deposition on the steep karstic topography rather than deformation.

More-recent karst features occur where residual blocks of Carawine Dolomite, preserved within the Pinjian Chert Breccia, have gradually dissolved causing the overlying Pinjian Chert Breccia to collapse and form a younger group of dolines or sinkholes. Such dolines occur several kilometres east of the Davis River manganese mines and 7.5 km south of Bee Hill.

Structure

The Fortescue and lower Hamersley Group rocks on BALFOUR DOWNS are deformed by curvilinear open folds with axes which swing from a north to an east-northeast trend across the sheet. Such folds include the Oakover and Noreena synclines and the Maggie and Kallona anticlines. The fold axes wrap around the southeastern margin of the Pilbara Craton (Trendall, 1983). An unusual S-shaped fold axis, the Rat Hill anticline (Rat Hill Rise, Goode 1981) trends southeast across BALFOUR DOWNS. This anticline is folded by the north to east-northeasterly trending curvilinear folds and is displaced by later faults.

Inliers of the Pilbara Craton, which form the basement of the Fortescue Group, are exposed along the Rat Hill anticlinal axis. The inliers consist of metamorphic rocks north of Stock Route Bore and post-tectonic granitoid rocks southwards from Stock Route Bore to the sheet boundary. The change in the basement lithology corresponds to a gradual southward thinning of the Fortescue - lower Hamersley Group sequence.

The basal unit of the Fortescue Group around the inliers is the Kylena Basalt with the exception of the Rooney Inlier which is unconformably overlain by the Mt Roe Basalt. This suggests that the palaeoerosion surface was relatively flat. Hence the Rat Hill anticline is not primarily due to a predepositional basement high. However, the Fortescue - lower Hamersley group sequence is thinner where it overlies granitoid basement, and this may be be due to the granitoid basement gently rising during deposition of the Fortescue - lower Hamersley sequence after the Kylena Basalt was laid down.

The Fortescue - lower Hamersley sequence is thickest where it overlies metasedimentary basement north of Stock Route Bore (i.e. Noreena syncline). This would support previous observations by Kriewaldt (1964) and Hickman (1983) that synclinal structures in the Fortescue Group tend to coincide with synformal greenstone belts in the underlying Pilbara Craton. The relationship of structures in the Pilbara Craton and the overlying Fortescue - lower Hamersley Groups is discussed by Trendall (1983).

The Fortescue Group and lower Hamersley Group are widely faulted on BALFOUR DOWNS. The earliest faults are steeply dipping growth faults which controlled deposition in some areas. Perhaps the most dramatic is a north-trending fault 6 km west of Sunday Hill which has influenced deposition of the entire Fortescue - lower Hamersley Group sequence. It may also have been operative during deposition of Manganese Group sedimentary rocks in a small basin at the Sunday Hills manganese prospect.

Vertical faults with a northerly trend and normal throw are abundant in the west and north of BALFOUR DOWNS. Some of them, such as the Russian Jack fault, contain major quartz reefs. These faults are intersected by a later east-northeast set of normal and possibly transcurrent faults which are concentrated in a zone about 40 km wide between Mt Divide and Balfour Downs homestead. Both sets of faults are attributed to basement block faulting. The east-northeast set may result from to instability along the margin of the buried Pilbara Craton.

The Pilbara Craton inliers, which lie along the Rat Hill anticline, are fault bounded on several sides. For this reason the inliers may be regarded as horsts or fault blocks rather than basement domes.

The similarity between the granitic rocks of the Springo and Cooninia inliers suggests a sinistral transcurrent movement along the Springo fault. Offset along this fault is in the order of 2.5 km. Other large faults of this type are the Tongololo, Cooninia, Whitewood and Balfour faults. All these faults have played an important role in the deposition and distribution of the Manganese Group sedimentary rocks.

Intrusive rocks

Several coarse-grained dolerite and gabbro bodies ($\underline{d_3}$) intrude the basal Jeerinah Formation 5 km northwest of Mt Lewin and 2 km north of Pippina Well. Similar bodies intrude the Nymerina Basalt 5 km northeast of Turkey Bore and 3.5 km north of Pulbah Well. A coarse-grained dolerite, intruding both the Kylena Basalt and granite of the Billinooka Inlier, is also grouped with these bodies. These intrusions show very low-grade greenschist facies metamorphism and are extensively altered to chlorite and carbonate. They are probably comagmatic with the closing stages of the mafic volcanic activity of the Fortescue Group.

An unusual suite of pink to grey, fine-grained to porphyritic dykes and small irregular bodies ranging from microcline-biotite trachyte to minette ($\underline{t}$) intrude the Fortescue and Hamersley Groups. Most of these intrusions occur around the Cooninia Inlier. The dykes intrude both the post-tectonic biotite adamellite of the inlier and the overlying Fortescue and Hamersley Groups. Several of these small bodies also intrude the Fortescue Group 1 km west of M48 Trig near the margin of the Rooney Inlier.

The dykes comprise microcline-albite-biotite and minor quartz with large accessory apatite and opaques. Hematite dusting is ubiquitous along grain boundaries and accounts for the distinctive pinkish hue of the rocks. It is widespread and may be of hydrothermal rather than weathering in origin.

Texturally the rocks range from fine-grained trachytic to porphyritic with euhedral microcline and/or biotite phenocrysts up to 4 cm long. These are set in a groundmass of microcline and albite microlites. The larger bodies are coarser grained and consist mainly of pink albite-microcline granite. They have contact metamorphic aureoles such as a carbonate-phlogopite (chloritized)-biotite skarn in Carawine Dolomite 4.5 km southwest of Brown Dam.

A single dyke of albite-hornblende lamprophyre (spessartite) intrudes the basal Jeerinah Formation 4 km southwest of Sunday Hill (de la Hunty, 1984). Hickman (1983) included this dyke in a north-northwesterly trending belt of small hornblende adamellite plutons that intrude the Fortescue Group on NULLAGINE. It is possible that the trachytic rocks around Cooninia Inlier may belong to this belt which would then be over 250 km long. These hornblende-adamellite bodies on NULLAGINE have given a preliminary Pb-Pb, whole-rock mineral isochron age of about 1700 Ma (Blake and McNaughton, 1984, p. 12). A Sm-Nd model T_{CHUR} age of 2411 $\pm$ 41 Ma (T_{MORB} 2861 $\pm$ 3 Ma) was obtained from a small porphyritic body 1 km west west of M 48 Trig.

BANGEMALL BASIN

De la Hunty (1966), Chuck (1984) and Muhling and Brakel (1985) have all suggested that the Manganese Group (de la Hunty, 1963), a sedimentary sequence which unconformably overlies the Hamersley Basin rocks on BALFOUR DOWNS, may occupy a northeasterly extension of the Bangemall Basin (Daniels and Horwitz, 1969). The remapping of

BALFOUR DOWNS in 1983-84 and recent remapping (1985) of the western half of the adjacent ROBERTSON sheet (Williams and Tyler, in prep) has found that the newly formalized stratigraphy, set up for the Manganese Group on BALFOUR DOWNS, can be followed southwestwards, around the eastern end of the Sylvania Inlier (Tyler, in prep) to the Weelarrana area in the southwestern corner of ROBERTSON. In this region correlation with Bangemall Basin stratigraphy on adjoining COLLIER and NEWMAN has been established. Additional support for this correlation lies in the similarity of well preserved Manganese Group stromatolites to those found and described from the Bangemall Basin (Grey, 1984). Davis (1977) reported an age of 1050 Ma for glauconite pellets from the Coondoon Formation in the Mount Divide area. However, because of the proximity of Davis Dolerite sills the date has also been interpreted as the time of dolerite intrusion (Goode and Hall, 1981).

The stratigraphic position of the Manganese Group with respect to other units in the area has been a matter of conjecture. The divergent opinions of the last decade, as to the age and stratigraphic position within the Precambrian, are summarized in Table 3.

Manganese Group

The Manganese Group is regarded as a lateral correlative of the Bangemall Group rather than a subgroup within the Bangemall Group as suggested by Muhling and Brakel (1985). The Manganese Group* occupies most of the southeast quadrant of BALFOUR DOWNS. In addition two narrow, partly

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*Subsequent remapping of these rocks on the adjoining ROBERTSON showed that they could be correlated with the Collier Subgroup of the Bangemall Group. The Muhling and Brakel proposal of Manganese Subgroup should therefore now be adopted.

TABLE 5. NEWLY DEFINED STRATIGRAPHIC UNITS

NAME	DERIVATION	TYPE AREA	THICKNESS, LITHOLOGY	AGE AND RELATIONSHIPS	REMARKS
YANDANUNYAH FORMATION	Yandanunyah Rock Hole 22° 22' 16" S 121° 14' 34" E	10km east-northeast of Canning Well 22° 20' 30" S 121° 24' 00" E	80m - interbedded dolomite, siltstone, shale	Rests conformably on Brownrigg sandstone Sandstone conformably overlain by Choorun Formation (Chin and others, 1980). Component of Yeneena Group.	Thin persistent unit but crops out irregularly.
BROWNRIGG SANDSTONE	Brownrigg Hill 21° 59' 44" S 121° 14' 34" E	9kms northeast of Canning Well 22° 20' 30" S 121° 23' 30" E	350m - medium to coarse-grained sandstone	Rests conformably on Waroongunyah Formation. Component of Yeneena Group.	Planar cross-beds, abundant asymmetric ripple marks. Forms prominent scarp.
WAROONGUNYAH FORMATION	Waroongunyah Rock Hole 22° 19' 07" S 121° 29' 10" E	8.5kms northeast of Canning Well 22° 20' S 121° 23' E	Max. 250m - interbedded dolomite, shale, siltstone, fine-grained sandstone, stromatolitic dolomite	Rests conformably on Googhenama Conglomerate; unconformably on Fortescue Group and Manganese Group. Component of Yeneena Group.	Stromatolitic bioherms similar to those found in the Waltha Warra Formation on Nullagine Sheet; also possible correlate of Wandy Wandy Shale, Nullagine Sheet.
WHITEWOOD FORMATION	Whitewood Bore 22° 51' 04" S 121° 39' 51" E	6km north of Whitewood Bore 22° 20' S 121° 23' E	+250m - coarse-grained sandstone, polymictic conglomerate lenses	Rests conformably on Balfour Formation. Component of Manganese Group.	Highest formation in Manganese Group on BALFOUR DOWNS. Restricted area of deposition.
BALFOUR FORMATION	Balfour Downs Homestead 22° 47' 48" S 120° 51' 28" E	Mt Trew area 22° 58' S 120° 39' E Milbeena Bore area 22° 10' S 120° 43' E	Max. 1500m - interbedded grey-green to red-maroon-chocolate shales, minor micaceous siltstone, calcareous and glauconitic sandstone.	Rests conformably on Enacheddong Formation and Stag Arrow Formation, possibly disconformable on Coondoon Formation, component of Manganese Group.	Combines Balfour Shale and Noreena Shale of de la Hunty (1963). Recent mapping has found distinction between shales invalid.
ENACHEDDONG DOLOMITE	Enacheddong Water Hole 22° 11' 57" E 121° 17' 47" S	4Km south-southeast Enacheddong Water Hole 22° 14' S 121° 18' E	0-300m - thin bedded, laminated multi-coloured dolomite, interbedded iron-rich shale and chert	Rests conformably on Stag Arrow Formation. Component of Manganese Group.	Distinctive banded photo-pattern, formation discontinuous, lensoid.
STAG ARROW FORMATION	Stag Arrow Well 22° 12' 27" S 121° 04' 37" E	10Km north-northwest of Canning Well 22° 17' S 121° 16' E	500-1500m - interbedded sandstone, siltstone, shale, conglomerate, dolomite and chert	Rests conformably on Woblegun Formation or unconformably on Hamersley Basin rocks. Component of Manganese Group.	Contains good stromatolite horizons in dolomite units.
WOBLEGUN FORMATION	Woblegun Hill 22° 12' 27" S 121° 04' 37" E	4Km and 12Km north northeast of Enacheddong Water Hole 22° 09' 121° 18', 22° 06' 121° 21'	0-280m - laminated shale, minor micaceous sandstone, pebble conglomerate and chert	Rests unconformably on Hamersley Basin rocks; basal unit of the Manganese Group.	Outcrops east of the Oakover River; lensoid, may correlate in part to the Coondoon Formation.
COONDOON FORMATION	Coondoon Creek 22° 05' S 120° 44' E	Just North of Coondoon Creek/Davis River Junction (de la Hunty, 1964) 22° 07' 30" 121° 45'	0-100m - poorly sorted sandstone, conglomerate, wacke, glauconitic sandstone, shale, minor dolomite	Rests unconformably on Hamersley Basin rocks, basal formation of Manganese Group in central part of BALFOUR DOWNS.	Distribution of formation controlled by palaeokarst topography developed on Carawine Dolomite and Pinjian Chert Breccia; incorporates Bee Hill Sandstone.

fault-controlled tongues of these rocks extend northward to the Sheet boundary in the central and eastern parts of the Sheet. The Manganese Group is unconformably overlain by the Yeneena Group in the northeast and by the Savory Group in the east, except where it is fault-bounded.

The previously defined component formations of the Manganese Group on BALFOUR DOWNS (de la Hunty, 1963) have been revised (see Table 1) as new fieldwork shows that the established formations do not adequately represent the rocks.

Two different stratigraphic sequences are recognized in the Manganese Group. The least extensive sequence consists of basal non-marine terrigenous sediments followed by sandy, shallow marine, and a transgressive marine shale. This sequence is restricted mainly to the central, partly fault-bounded tongue of sedimentary rocks which lie north of the Tongololo fault complex in the central part of BALFOUR DOWNS. It extends from the Tongololo fault northward towards Bee Hill and Hawkins Bore. Similar sedimentary sequences occur in small fault-controlled basins, near Ant Hill and at the Sunday Hill Manganese prospect. This sequence was deposited on an irregular, well established palaeokarst topography formed within the Carawine Dolomite and associated Pinjian Chert Breccia (Davis, 1977).

Locally derived, fine to coarse-grained sedimentary rocks occur in numerous dolines, poljes and karst valleys. The sedimentary rocks become finer grained upwards, and these separate small basins were probably coalesced into a single basin by a marine transgression which deposited the upper shale unit.

Manganese Group. It lies to the south and east of the first sequence. It can also be traced for over 150 km south-southwest where it can be correlated with known Bangemall Group stratigraphy on COLLIER and NEWMAN (Williams and Tyler, in press). The second sequence consists of epiclastic and carbonate shelf deposits overlain by shale (distal turbidite) interpreted as marginal deposits of an intracratonic basin. This shale is stratigraphically equivalent to the shale that caps the first sequence in the central part of BALFOUR DOWNS. Although these two sequences are largely coeval, the second sequence is much thicker south of the Tongololo fault complex.

The newly defined and revised formations are described in detail in Table 5.

Coondoon Formation (MNc)

The newly defined Coondoon Formation replaces the Coondoon Conglomerate and Bee Hill Sandstone (de la Hunty, 1963). It is equivalent to the 'red bed' sequence which comprised the lower part of the informally named Shag Pool Formation (Davis, 1977). The Coondoon Formation is restricted to, and is the basal unit of, the fault-bounded sequence north of Tongololo Fault in the central part of BALFOUR DOWNS.

It occurs in small scattered outcrops and consists of boulder conglomerate, coarse-grained sandstone, wacke, siltstone and shale. The stratigraphy shows great variation from place to place and the thickness ranges up to 100 m. It rests unconformably on an eroded karst topography of Carawine Dolomite and Pinjian Chert Breccia. The lowest conglomerate mainly contains clasts of Pinjian Chert Breccia where it offlaps larger areas of that unit, but also occurs as a thin (>1 m) bed overlying the

Fortescue Group where the clasts are largely chalcedonic silica and agates. Manganiferous, chocolate, black, and maroon shales also form a basal unit in many of the dolines and poljes within the Carawine Dolomite and Pinjian Chert Breccia. The conglomerate and shales are overlain by thick, cross-bedded, red-brown sandstone and quartz-wacke, some of which contain heavy mineral bands (de la Hunty, 1963; 1964).

The top of the formation consists of a distinctive grey-green medium to coarse-grained pelletal glauconitic sandstone. Good exposures occur at Ant Hill and 4 km southeast of Mount Cooke.

Woblegun Formation (MNw)

The newly defined Woblegun Formation (see Table 1), is only exposed east of the Oakover River in a fault-bounded north-trending tongue of the Manganese Group. It is the basal unit of the marine shelf sequence. It unconformably overlies flat-lying Carawine Dolomite and Pinjian Chert Breccia. The formation also infills small grabens developed in the block-faulted Carawine Dolomite along Googhenama and Enacheddong Creeks.

The formation consists of grey-white, white and green shale and silty shale with minor red shale, fine-grained sandstone, polymictic conglomerate and chert. Pelletal glauconite occurs in quartz sandstone and in a distinctive green siliceous shale some of which has a high carbonate content. Relic evaporite minerals (gypsum) occur in some cherts. The predominantly fine-grained nature of the rocks, together with the presence of pelletal glauconite and evaporite minerals, indicate quiet, shallow-marine and possibly coastal-sabkha conditions.

Stag Arrow Formation (MNs)

The newly defined Stag Arrow Formation (Table 1) crops out throughout the southeast part of BALFOUR DOWNS from Enacheddong Creek south to the Sheet boundary and west to Tony Bore. It conformably overlies the Woblegun Formation in the Canning Well - Enacheddong Creek area but west of the Oakover River it rests unconformably on the Fortescue and Hamersley Groups and the granitoid Billinnooka Inlier of the Pilbara Craton.

Although the formation includes a wide variety of rock types, sandstone is dominant. Rock types range from polymictic and quartz pebble conglomerate, and coarse sandstone near the base, which resemble rocks of the Coondoon Formation, to fine-grained quartz sandstone, siltstone and shale. Glauconitic sandstone, feldspathic sandstone, quartz wacke and chert are minor components. The chert contains unusual textures which may represent pseudomorphs of evaporitic minerals such as gypsum. Massive to well-laminated yellow-grey-weathering dolomite occurs at the top of an upward-fining sequence of conglomerate, sandstone and shale.

Stromatolites occur in the Enacheddong Water Hole - Canning Well area, 8 km north of Balfour Downs homestead and 6 km north of Laurie Bore. They may be domical, columnar or conical, and form distinct horizons, traceable for several kilometres. Secondary silicification is common at some localities and interspaces between columns are sometimes infilled with gossanous material (after pyrite, manganese oxide and scattered glauconite).

Columnar forms occur as 2 m-high bioherms with widely spaced columns. Near Laurie Bore they occur in dark grey-blue dolomite; similar columns elsewhere occur in brownish-yellow dolomite. Conical stromatolites -

Conophyton f.indet. - form successive biostromes in reddish dolomite in the Canning Well area. They indicate growth below wave-base, probably in at least 2 m of quiet water (Grey, 1984).

The stromatolitic dolomites are regionally distributed along the northwest margin of the Manganese Group and are probably close to the original shoreline of the basin in which the Manganese Group was deposited. The Stag Arrow Formation is interpreted as a shallow marine, stable shelf deposit.

Enacheddong Dolomite (MNe)

The newly defined Enacheddong Dolomite conformably overlies the Stag Arrow Formation (Table 4). The formation is lenticular and ranges from 0 to 300 m thick. It is best developed in the Enacheddong Water Hole - Canning Bore area from where it extends southwestward to the Bullstag Well area. It also occurs near Deep Bore on the southern boundary of the sheet.

The term 'Enacheddong Formation' was previously used informally (Goode, 1981) to describe carbonates in the Manganese Group east of the Oakover River. The newly-defined formation is now restricted to a carbonate unit with a distinctly striped photo-pattern which can be traced at least 160 km to the southwest of Enacheddong Water Hole (Williams and Tyler, in press).

The formation consists of multicoloured banded, massive to laminated, very fine-grained dolomite, dolomitic calcilulite and shale. Minor banded chert also occurs. The massive dolomite is thick-bedded and dark-grey to dark-brown, while the laminated dolomite is light-grey, pink, grey-green and buff. Locally, half of the total thickness of the formation is shale. Chert and red iron-rich shale occur at the base of the formation. Some dolomitic breccia is also present but stromatolites appear to be absent.

The formation was deposited on a gentle slope possibly marginal to a deep water basin. The Enacheddong Dolomite is thickest adjacent to the main stromatolitic dolomite of the Stag Arrow Formation, particularly in the Enacheddong Water Hole area.

Balfour Formation (Mnb)

The newly defined Balfour Formation replaces the previously mapped Balfour Shale and Noreena Shale of the Manganese Group (de la Hunty, 1963). A reassessment of these shales has found that although they are morphologically distinct they are intimately interlayered, reflecting changing depositional environments (oxidizing and reducing conditions) within a single formation rather than being separate stratigraphic units.

Chocolate, red-brown and deep purple shale, with some braunite pellets (de la Hunty's Noreena Shale) predominates in the northern part of the Balfour Formation and is well exposed in the Ant Hill, Mount Cooke and Turummunda Rock Hole areas. This shale is interbedded with green to grey-green shale (de la Hunty's Balfour Shale) which becomes dominant to the south and forms the bulk of the Balfour Formation in the Balfour Downs homestead, Mount Trew, Scott Bore, Canning Well and Wadra Hills areas. The grey-green shale contains thin interbedded micaceous, calcareous and glauconitic siltstone horizons. The shale also contains high concentrations of manganese in the basal portions which conformably overlie the Enacheddong Dolomite.

The Balfour Formation is extensively intruded by sills of fine-grained Davis Dolerite, particularly in the Mount Trew, Mount Divide, east of Mount Cooke and Wadra Hills areas.

Whitewood Formation (Mnh)

The newly defined Whitewood Formation conformably overlies the Balfour Formation. The formation is restricted to small areas adjacent to and south of the large Whitewood fault. The main exposures lie about 15 km northwest and 20 km southwest of Balfour Downs homestead. These outcrops were previously correlated with the Googhenama Conglomerate (de la Hunty, 1963).

The formation consists of cross-bedded, coarse-grained lithic and quartz sandstone with some interbedded cobble conglomerate. Clasts are derived from the adjacent Fortescue and Hamersley Group rocks together with a granitic component from the nearby Cooninia Inlier.

The association of conglomerate with quartz sandstone rather than turbidites suggests that the formation represents an encroaching alluvial-fan rather than submarine-fan deposits. The Whitewood Fault appears to have been an active growth fault during deposition of the Manganese Group.

Structure

The northern limit of the Manganese Group is extensively controlled by faulting. Some of the large east-northeast trending faults, such as the Whitewood and Tongololo Faults, could be reactivated listric growth faults. The occurrence of the coarse-grained epiclastic Whitewood Formation adjacent to the Whitewood Fault suggests that this fault may have been active during its deposition.

Small isolated basins, containing Manganese Group and surrounded by Fortescue Group rocks, are related to north-trending faults in the Sunday Hills and Ant Hill areas. A narrow zone of Manganese Group which extends north from the Tongololo Fault zone to the Coondoon Creek and Bee Hill areas is largely fault bounded. This graben-like structure resembles an aulocogen opening to the south. This zone crosses older structural trends in the Fortescue - lower Hamersley Group almost at right angles. A tensional regime characterizes the deposition of the Manganese Group.

The eastern margin of the Manganese Group northeast of Christies Crossing is abruptly terminated by a north-trending steep reverse fault (east side up), the Canning Fault. This fault has upthrusted Fortescue Group basalts against Balfour Formation.

In the southeast corner the north-northeasterly trending Millarie Fault zone terminates the Manganese Group against the Savory Group. There appears to be a dextral transcurrent movement on this fault zone.

The east-northeasterly trending Tongololo Fault zone marks the southern limit of the basal Coondoon Formation. The fault zone may reflect a local hinge line between shallow water to the north and deeper water to the southeast.

The Manganese Group is gently folded in the area between Balfour Downs homestead and Christies Crossing on the Oakover River. Here open folds have short but sinuous axes which tend to be unidirectional within fault-bounded domains. This suggests that the folding and faulting are related and can possibly be attributed to basement block movement.

In contrast, tight asymmetrical and overturned folds, with axial planes dipping northeast, occur east of Wadra Hills. In this region and also east of Christies Crossing the shale units have developed an incipient axial planar cleavage.

The steep reverse faulting, development of an incipient cleavage, and overturned folds, are the products of a compressional tectonic regime which has its origin in the adjacent younger Paterson Orogen which lies to the northeast.

Intrusive rocks

Davis Dolerite (dd)

The Davis Dolerite is fine to very fine-grained with a high (up to 4 per cent) titaniferous magnetite content which gives it a distinctive black, speckled weathered surface and a strong magnetic expression. Secondary minerals include chlorite, biotite and amphibole. Pumpellyite and general alteration in the dolerite suggest very low-grade static metamorphism.

The dolerite occurs mainly as shallow sills which mostly intrude the Balfour Formation but are also present in the lower Coondoon and Stag Arrow Formations. Feeder dykes have been recognized in the Davis River area.

In many cases the Davis Dolerite forms the uppermost exposed unit within the Manganese Group. This has led to the suggestion that some mafic material may be extrusive (Davis 1977). No evidence was found to support this proposal. Contact metamorphic hornfels has been found in shale both above and below the dolerite bodies. Large sills of Davis Dolerite occur east of Mount Cooke, in the Mount Divide area southeast of Turummunda Rock Hole, and around Mount Trew.

A medium to coarse-grained green to white speckled dolerite occurs in the Wadra Hills. This dolerite also intrudes the Balfour Formation. It may represent a separate suite or a more deeply emplaced intrusion of Davis Dolerite.

PATERSON OROGEN

The late Precambrian Paterson Orogen, which lies to the east of the Pilbara Craton, contains two major components: the Rudall Complex (Rudall Metamorphic Complex, Williams and others, 1976); and a late tectonic cover sequence, the Yeneena Group, (Williams and others, 1976).

Gently folded and faulted sedimentary rocks of the Yeneena Group occupy a small area in the northeast corner of BALFOUR DOWNS. In this area the group consists of six formations and rests unconformably on the Gregory Granitic Complex, Hamersley Basin sedimentary and volcanic rocks, and the Manganese Group (Bangemall Basin). It is, in turn, unconformably overlain by the flat-lying Savory Group.

The Yeneena Group, on adjoining PATERSON RANGE and RUDALL, has been described as a marine-shelf sequence (Chin and others, 1980; Chin and others, 1982). The upper two formations on BALFOUR DOWNS, the Isdell and Choorun Formations, can be directly correlated with these previously defined units on adjoining RUDALL. However, the lower formations, the newly defined Yandanunyah, Brownrigg and Waroongunyah Formations and the previously defined Googhenama Conglomerate (de la Hunty, 1963) are not directly equivalent to units established on adjoining RUDALL and PATERSON RANGE.

The Yeneena Group on BALFOUR DOWNS consists of coarse-grained clastic sequences alternating with fine-grained clastic and carbonate sequences which are interpreted as high and low-energy environments. These are also interpreted as shallow marine-shelf deposits, which received coarse-grained terrigenous material from the west at regular intervals.

Yeneena Group

Googhenama Conglomerate (Yg)

The basal Googhenama Conglomerate (de la Hunty, 1963) is a polymict, boulder (up to 1.5 m) to pebble conglomerate grading to a coarse-grained sandstone at the top. The formation unconformably rests on the Gregory Granitic Complex and the Hamersley and Manganese Groups. The unit can be traced from the BALFOUR DOWNS boundary in the northeast corner southward to just east of the Enacheddong Water Hole. Here the formation lenses out and is transgressed by the overlying Waroongunyah Formation.

The conglomerate is poorly sorted with both clast and matrix-supported types. Clast lithologies are quartzite, chert, vein quartz and granitoids. The chaotic appearance of the conglomerate suggests debris flows either in an alluvial-fan or near-shore submarine-fan environment. The sandstone component becomes dominant northwards and the conglomerate is restricted to basal lenses. This formation has been called the Bocrabee Sandstone on NULLAGINE (Hickman, 1978), but this term should be dropped. The current stratigraphic revision on BALFOUR DOWNS has shown that the Bocrabee Sandstone, as defined by de la Hunty (1963), is a composite unit which is now known to include sandstone units which form part of the Manganese, Yeneena and Savory Groups.

Waroongunyah Fomration (Yw)

The Waroongunyah Formation rests unconformably on the Fortescue Group, which forms a basement high in this region, and conformably on the Googhenama Conglomerate. The formation may be correlated with the poorly outcropping Wandy Wandy Shale (Hickman, 1978) which overlies the Bocrabee Sandstone on NULLAGINE.

The formation comprises laminated to thin-bedded pink and grey dolomite, sandy dolomite and stromatolitic dolomite interbedded with purplish-brown to buff shale, siltstone and fine-grained sandstone. Where the formation rests directly on the Fortescue Group a dolomitic cemented, polymict conglomerate occurs at the base. This conglomerate contains a mixture of clasts derived from the underlying mafic and felsic volcanic rocks of the Fortescue Group.

Well-formed stromatolitic bioherms occur 7 km southeast of Canning Well. Preliminary studies indicate similarity with taxa found in the Waltha Woora Formation (Hickman, 1978) on NULLAGINE to the north (Grey, 1984, 1986),

The carbonate component is unevenly distributed through the formation with the main outcrops occurring in the southern exposures east of Canning Well. Fine-grained clastic rocks make up the bulk of the formation in the headwaters of Googhenama Creek. Ripple-marked bedding is a prominent feature of this formation.

Brownrigg Sandstone (Yr)

The Brownrigg Sandstone is a uniform, flaggy to thick-bedded, well-sorted, medium to coarse-grained, red-brown, quartz sandstone. The formation forms prominent cliffs or scarps above the easily erodable Waroongunyah Formation upon which it rests conformably.

Planar cross-beds and abundant asymmetric ripple-marked bedding characterize the formation. The unit is interpreted to be a shallow-marine sand.

Yandanunyah Formation (Yy)

The Yandanunyah Formation is a thin, but persistent, poorly outcropping, mixed clastic-carbonate formation which rests conformably on the Brownrigg Sandstone. It consists of pink to grey laminated dolomite, calcareous siltstone and shale. Microbial banding occurs although unequivocal stromatolites were not recognized in the dolomite. The formation is a finer grained version of the underlying Waroongunyah Formation. It is probably a deeper water deposit which formed farther from the shoreline than the underlying formation.

Choorun Formation (Yh)

The Choorun Formation (Williams and others, 1976) is the thickest formation of the Yeneena Group on BALFOUR DOWNS and lies conformably on the Yandanunyah Formation. It resembles the western facies of the same formation described on RUDALL (Chin and others, 1980). It consists of randomly interbedded, red-brown, fine to medium-grained sandstone, white flaggy orthoquartzite, micaceous siltstone and white to grey shales. Small-scale cross-beds are present and symmetric and asymmetric ripples are abundant.

The sandstone unit forms cliffs and the formation is characterized by a series of strike ridges with shale and siltstone occupying valleys between sandstone units.

Isdell Formation (Yi)

The Isdell Formation (Williams and others, 1976) crops out near the northeast margin of BALFOUR DOWNS. It is separated from the Choorun Formation by the Marloo Fault but elsewhere it has been shown (Chin and others, 1980) to lie conformably on the Choorun Formation. The sequence consists of fine to coarse-grained thin-bedded to laminated, pink, grey and buff clastic dolomites and stromatolitic dolomites interbedded with coarse-grained sandstone and pebble conglomerate horizons (Yi(a)). Some of these latter units are sand and pebble-filled scour channels within marine-shelf carbonates. Stromatolitic dolomite occurs 25 kms north-northeast and 20 km northeast of Canning Well. Preliminary studies indicate that forms in the Isdell Formation resemble those found in the Waltha Woora Formation on NULLAGINE (Grey, 1984, 1986).

Structure

The Yeneena Group is characterized by steep reverse faults and open asymmetric folds with axial planes dipping steeply east. Both indicate east-west compression. No cleavage was detected in the Yeneena Group rocks. An unnamed fault along the western side of the Gregory Granitic Complex and the north-trending Canning and Marloo Faults are also steep reverse faults with upthrow of the eastern block. An unnamed west-trending reverse fault, 6 km north of Bocrabee Hill, has thrust Yeneena Group rocks south over the Savory Group.

SAVORY BASIN

Savory Group

The newly recognized Savory Group, described in detail on ROBERTSON (Williams and Tyler, in press) is a flat-lying, faulted, arenaceous sequence which occupies a small area on the southeast corner of BALFOUR DOWNS. The group unconformably overlies sedimentary rocks of both the Manganese Group (Bangemall Basin) and Yeneena Group (Paterson Orogen). This revised stratigraphy replaces the previous interpretation which regarded the sandstone in the southeast corner of BALFOUR DOWNS as part of the Calyie Sandstone. The Calyie Sandstone was part of the eastern facies (Collier subgroup) of the Bangemall Group (Brakel and Muhling, 1976), Muhling and Brakel, 1985). Previously de la Hunty (1963) had incorporated this sandstone in the now superseded Bocrabee Sandstone (see section on Googhenama Conglomerate).

Only the two lowest formations of the Savory Group, the Watch Point and Coondra Formations, are present on BALFOUR DOWNS.

The crucial area on BALFOUR DOWNS which supports the new stratigraphy, lies 22 km east of Christies Crossing and 7 km north of Bocrabee Hill. Here the Coondra Formation of the Savory Group lies with a well-exposed, low-angle (15^{o}) unconformity upon the Choorun Formation of the Yeneena Group. The Coondra Formation at this locality contains scattered cobbles and pebbles derived from the underlying Choorun Formation orthoquartzite. In addition, pebble conglomerate lenses 14 km east of Cockatoo Springs and boulder conglomerate beds 14 km southeast of

Melon Well contain mixed clasts which can be identified with lithologies found in the underlying Manganese Group (Bangemall Basin).

The contact between the Savory Group and the Manganese Group is largely masked by sand. However east of the Wadra Hills the sequences are separated by the Millarie Fault complex.

Coondra Formation

The Coondra Formation mainly consists of planar and trough cross-bedded, red-brown quartz sandstone containing scattered, rounded pebbles and small lenses of pebble or cobble conglomerate. Siltstone and fine-grained sandstone intraclasts are abundant in some horizons. Cross-beds form sets up to 8 m thick and indicate current directions mainly from the west. The quartz sandstone passes laterally into purple-brown and purple-grey quartz and lithic wackes (Cy(w)) in the Woora Woora Hills area.

Watch Point Formation

At Bocrabee Hill the Coondra Formation is conformably underlain by brown shale, laminated micaceous siltstone and white fine-grained sandstone (Cy(s)) which are correlated with the Watch Point Formation on ROBERTSON (Williams and Tyler, in press).

The Savory Group in this area is interpreted as a tidal-swept, shallow-marine sand close to, and fed by, a high-energy delta system.

The Savory Group is intruded by a suite of north to north-northeasterly trending dolerite dykes (d_4) most of which are now weathered to white clay.

Structure

The Savory Group is generally flat-lying. It is folded into very broad open synclines west of Marloo Rock Hole and south of the Woora Woora Hills. Movement along the Millarie Fault, which separates the Savory Group from the Manganese Group, is dextral transcurrent. Fault zones in the Savory Group are accompanied by kinking of the sandstone. These fault zones are generally compressional with east to west movement.

PHANEROZOIC ROCKS

PERMIAN

Paterson Formation (Pa)

Following Hickman (1978), the Paterson Formation (Traves and others, 1956) incorporates and replaces the previously mapped basal Braeside Tillite and overlying arenaceous Bunmardie Beds (de la Hunty, 1964) on BALFOUR DOWNS. There are no exposures in situ of the basal tillite but boulder fields, which extend northward from the vicinity of the Enacheddong water hole to the sheet boundary, indicate that the unit was formerly widespread. A similar conglomerate, loosely held in a sandy clay matrix, extends for about 15 km along Coondoon Creek, north from the junction with the Davis River.

In both areas the boulders range in size up to 1.5 m across, are unsorted, faceted and some are striated. Boulders include the local Precambrian rock types such as granite, gneiss, basalt, quartzite and various silicified sedimentary rocks. The semi-consolidated boulder beds have been mapped as Qt.

The upper part of the formation, previously mapped as Bunmardie Beds, occurs as small mesas of massive and cross-bedded, clayey, quartz sandstone. The sandstone is moderately sorted and contains clay balls and thin shale lenses.

Recent erosion of the Paterson Formation (exemplified 3 km southeast of Enacheddong water hole) has revealed poorly preserved glaciated pavements.

CAINOZOIC

Oakover Formation (To)

The Oakover Formation (Noldart and Wyatt, 1962) comprises a distinctive vuggy, white to grey, opaline-silica caprock overlying bedded grey limestone, sandy limestone and calcareous sandstone. The unit is up to 35 m thick and where strongly dissected forms prominent scarps, mesas and buttes. The formation is closely associated with the present-day Oakover River drainage and its major tributaries, the Davis River and Noreena Creek. The formation can also be traced across the major divide between Noreena Creek and Kulkinbah Creek which lies in the headwaters of the north branch of the Fortescue River.

Where the Oakover Formation merges with the present ground level it is generally capped by younger calcrete. The formation appears to be a lacustrine-fluvial deposit modified by later chemical precipitation of calcrete and silica. The large areas of Oakover Formation shown in the Fortescue River Valley on the first edition of BALFOUR DOWNS were found instead to consist of lacustrine and eolian deposits of clay, silt and sand distributed in clay pans separated by intervening low sand dunes (Qd). However the possibility that the Oakover

Formation underlies the Qd unit cannot be discounted since calcrete is exposed near Five Mile Bore in the Fortescue River Valley near the western margin of the sheet area.

Trunk-valley calcretes (Butt and others, 1977) (Czk) occur in a number of major drainages, particularly in sand-buried drainage lines east of the Oakover River.

The Oakover Formation is interlayered with older colluvium (Tc) along Noreena Creek. The Tc unit is very crudely bedded and consists of semi-consolidated ferruginous silt, sand and gravel. This Tc unit is capped along the main drainage divides by ferruginous duricrust and laterite. Several ages of laterite may also be present as de la Hunty (1964) recorded limonite deposits beneath the Oakover Formation. Massive, nodular and pebbly laterite (Tl) caps weathered basalt along the main divide between the Fortescue and Oakover River drainages.

Chert breccia and mixed siliceous caprock (Tb) form a siliceous duricrust over Carawine Dolomite and Pinjian Chert Breccia in the Davis and Oakover River valleys. Low sinuous mesas of pisolitic limonite (Tp) mark ancestral-drainage lines along the Nullagine River and in the Kurrana Creek area.

A distinctive ferruginous duricrust (Td) overlies the iron-rich Marra Mamba Formation. It resembles the 'Hamersley Surface' (Campana and others, 1964) and has been extensively prospected for iron and manganese in the Mount Nicholas, Mount Cooke and Mount Rove areas.

Superficial deposits (Quaternary) can be broadly categorized as alluvial, colluvial, eluvial and eolian deposits although distinct morphological units tend to be mixtures of the above units.

Alluvial deposits include unconsolidated silt, sand and gravel of the ephemeral creeks and river beds, and clay, silt and sand of the adjacent flood plains (Qa).

East of Wadara Range large clay pans, some fresh and others saline, contain silt and clay deposits (Ql). The larger clay pans are surrounded by a mixed lacustrine - eolian deposit consisting of low anastomising sand dunes surrounding small clay pans (Qd). This unit is also widespread in the low-gradient Fortescue River valley.

Closely associated with Qd is a low-slope colluvial unit of mixed gilgai and gravel flood plain (Qr). This unit is part of the broad flood fans formed by tributaries of the Fortescue River.

A distinctively striped, low-slope, sheet-wash, colluvial unit (Qw) lies adjacent to the main drainages and is easily distinguished on air-photos. It consists of parallel bands (at right angles to sheet flow) of mulga (*Acacia* sp) separated by generally bare sand or gravel-covered pans.

Other colluvial units include: sand and gravel on slopes adjacent to fresh bedrock (Qc); partly ferruginized silt, sand and gravel overlying a clay hardpan (Qe) which forms on, and is derived from, the Tertiary units Tc and Tb; and gravel and boulders set in a clay matrix (Qt) which is formed specifically over eroded remnants of the Permian Paterson Formation.

An eluvial gilgai or 'crabhole' unit (Qb), sometimes containing fresh rock fragments and boulders, occurs over basalt, dolerite and some shales.

Eolian deposits range from red seif (longitudinal) and net dunes to red and red-brown sand sheets (Qs). Some sand sheets (Qp) are mixed with, and have a thin veneer of, ironstone pebbles. The source of the ironstone pebbles is attributed to weathering of Tl and Tc units. Most sand-dune country lies east of the Oakover River although some seif dunes occur on sandplains in the vicinity of Ethel Creek homestead.

ECONOMIC GEOLOGY

No large-scale mining has taken place on BALFOUR DOWNS, but small to moderate tonnages of manganese and ferromanganese ore have been produced from a number of open-cut operations. The manganese ore mined from BALFOUR DOWNS contributed significantly to the State's total production before 1970. Very small amounts of copper ore and minor alluvial gold and eluvial and alluvial tin, beryl and tantalite/columbite have also been won. Minor uranium occurrences and tanteuxenite-bearing pegmatites have been prospected. Corundum, diaspore and barite have been recorded.

Water supplies were not investigated in the present survey but de la Hunty (1964) recorded some observations.

MANGANESE

The discovery, exploration (from the mid 1950's), and early production of manganese in the BALFOUR DOWNS area is described by de la Hunty (1963). Subsequent exploration, with reassessment of known deposits has been described in de la Hunty (1965), Giesecke (1966), Blockley (1975), Davis (1977), Hickman (1983) and many unpublished exploration-company reports held at the Geological Survey of Western Australia.

The Ant Hill, Mount Cooke, Davis River and Bee Hill areas were the main producers of manganese ore. Up to 1977 production amounted to 562 657.20 t with an average grade of 49% Mn (Hickman, 1983). Ferromanganese ore was mined from the vicinity of Mount Nicholas and Mount Fraser (Limestone Well).

A large unworked ferromanganese deposit (proven ore, 167 Mt at 47.0% Fe, 6.9% Mn) occurs at Mount Rove (Giesecke, 1966). A low-grade manganese deposit (inferred tonnage 1.7 Mt of 30% to 40% Mn) occurs at Booginia Hill, 4 km northeast of Balfour Downs homestead (de la Hunty, 1963).

The manganese ore deposits occur as thin cappings, irregular blocky deposits, cave and fissure (joint) fillings, as loose and cemented pisolites and in sedimentary beds with a high manganese content enriched by weathering processes (de la Hunty, 1963).

More recently Davis (1977) pointed out the close relationship between manganese deposits and a complex palaeokarst topography in the Carawine Dolomite. This erosion surface has in turn influenced later sedimentation patterns for both the Pinjian Chert Breccia and the younger Manganese Group. Both sequences are host to manganese deposits.

Goode (1981) classified the deposits in terms of replacement of: the Carawine Dolomite; Pinjian Chert Breccia; and the basal shales of the Manganese Group. However recent remapping has now shown that not all shales that are enriched in manganese are basal. Manganese-enriched shales of the Balfour Formation which occur at Booginia Hill overlie dolomite units of the Stag Arrow Formation and not the Carawine Dolomite as previously mapped.

Another category of deposit is the secondary enrichment of manganiferous shale units in the Marra Mamba Iron Formation.

The main type of manganese deposit in the Davis River, Mount Divide and Bee Hill areas is replacement and cavity infilling of the Carawine Dolomite and Pinjian Chert Breccia. These deposits are small, podiform or irregularly shaped but are generally high grade (mineralization is pyrolusite, psilomelane and cryptomelane). Enriched shales of the Manganese Group, typified by the Booginia Hill deposit, are larger sheet-like deposits but with lower grade mineralization: braunite, bixbyite, pyrolusite and cryptomelane. Finally, mineralization associated with the Marra Mamba Iron Formation is generally ferromanganese with the Fe content (hematite, limonite, goethite) higher than the Mn content (pyrolusite, jacobsite). Such deposits include Mount Nicholas, Mount Fraser and Mount Rove.

Mount Cooke, Ant Hill and Sunday Hill deposits are mixtures of the above categories.

COPPER

Small copper deposits have been known and prospected for over 75 years (Talbot, 1920). The best known and main producer is the Blowhole deposit (also called Mount McLarty, Saddleback or Tubuddabudda deposit) which lies 6 km north of Saddleback Hill. A second very small producer, the Turummunda deposit, lies 1 km northeast of Turummunda rock hole. Six other small copper prospects occur within 11 km of the Turummunda deposit.

Total production is small with 178.56 t of cupreous ore averaging 20.43% Cu for the 1958-1965 period. Further information can be found in de la Hunty (1964) and Marston (1979).

All these deposits are probably supergene. The copper mineralization occurs in shear zones, along joint and fault planes and filling small cavities and cave breccia in the Carawine Dolomite.

Recent investigations of the Turummunda deposit suggest that the copper mineralization may be stratabound within a reddish shale overlain by dolomite. This sequence probably belongs to the Coondoon Formation of the Manganese Group. The copper has possibly been leached from nearby Davis Dolerite or underlying Fortescue Group basalts by meteoric waters and redeposited in suitable fractures or favourable beds. Mineralization includes malachite, azurite, chrysocolla, atacamite and cuprite. Chalcocite occurs in the Turummunda deposit.

Interest in the copper potential of BALFOUR DOWNS has been renewed following the discovery of the Nifty deposit by Western Mining Corporation on PATERSON RANGE. Exploration now centres on sediment-hosted stratabound copper deposits (Zambian-style stratabound type).

Copper mineralization, associated with sedimentary sequences, occurs at the Turummunda deposit and 3 km east of Enacheddong water hole in a faulted part of the Googhenema Conglomerate at the base of Yeneena Group.

GOLD

Small amounts of alluvial gold have been won from Rooneys Find (9 km northwest of Brown Dam) and another locality 1 km northeast of Sunday Hill. Both occurrences are in superficial colluvial material derived from the basal conglomerates of the Hardey Sandstone. Several shallow shafts have been sunk in a quartz-filled shear zone in quartz-muscovite schist in the Rooney Inlier close to the old alluvial workings. The surface layers of colluvial gravel at the base of Sunday Hill have been bulldozed and removed for treatment. No production has been recorded from either site.

URANIUM

Small quantities of radioactive rare-earth minerals such as tanteuxenite have been recorded from tin/tantalite-bearing pegmatites in the Upper Five Mile Creek area.

The basal Hardey Sandstone has been explored for uranium in the quartz-pebble conglomerates in the Turkey Bore - Rooney's Find area and arkosic grit and clay overlying granite has been investigated 3 km northwest of Koonmoonboonah Well. No mineralization of any consequence has been discovered.

PEGMATITE MINERALIZATION

Blockley (1980) reported that small quantities of tin, tantalite/columbite and beryl were produced from the Upper Five Mile area in 1955. The workings appear to be mainly shallow alluvial. Hickman (1983) reports 2.4 t of $(Ta,Nb)_2O_5$ from this area.

Small pits in layered albite pegmatite near the edge of the Bonnie Downs Granite, 5 km east of Haystack Well, have produced some tantalite (Hickman, 1983).

Tin has also been produced from the upper reaches of Daylight Creek, about 19 km south of Nullagine, east of the Great Northern Highway (Blockley, 1980).

CORUNDUM (EMERY)

Emery deposits occur in several prominent outcrops 2 km southwest of Rat Hill in the Rat Hill Inlier. The fine- to medium-grained corundum rock is associated with muscovite and rutile. A prominent feature of this deposit is the presence of sky-blue crystalline diaspore in joint fillings and veins.

BARITE

De la Hunty (1964) recorded barite in quartz veins north of Turkey Bore (24 km east of Rat Hill). This locality was not found. A barite-bearing skarn occurs 4.5 kms west-southwest of Brown Dam.

GEMSTONES

Prase and fuchsitic quartzite occur 10 km northwest of Noreena Downs homestead. Agates and carnelian are abundant in the upper parts of the Nymerina and Kylena Basalts throughout BALFOUR DOWNS.

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